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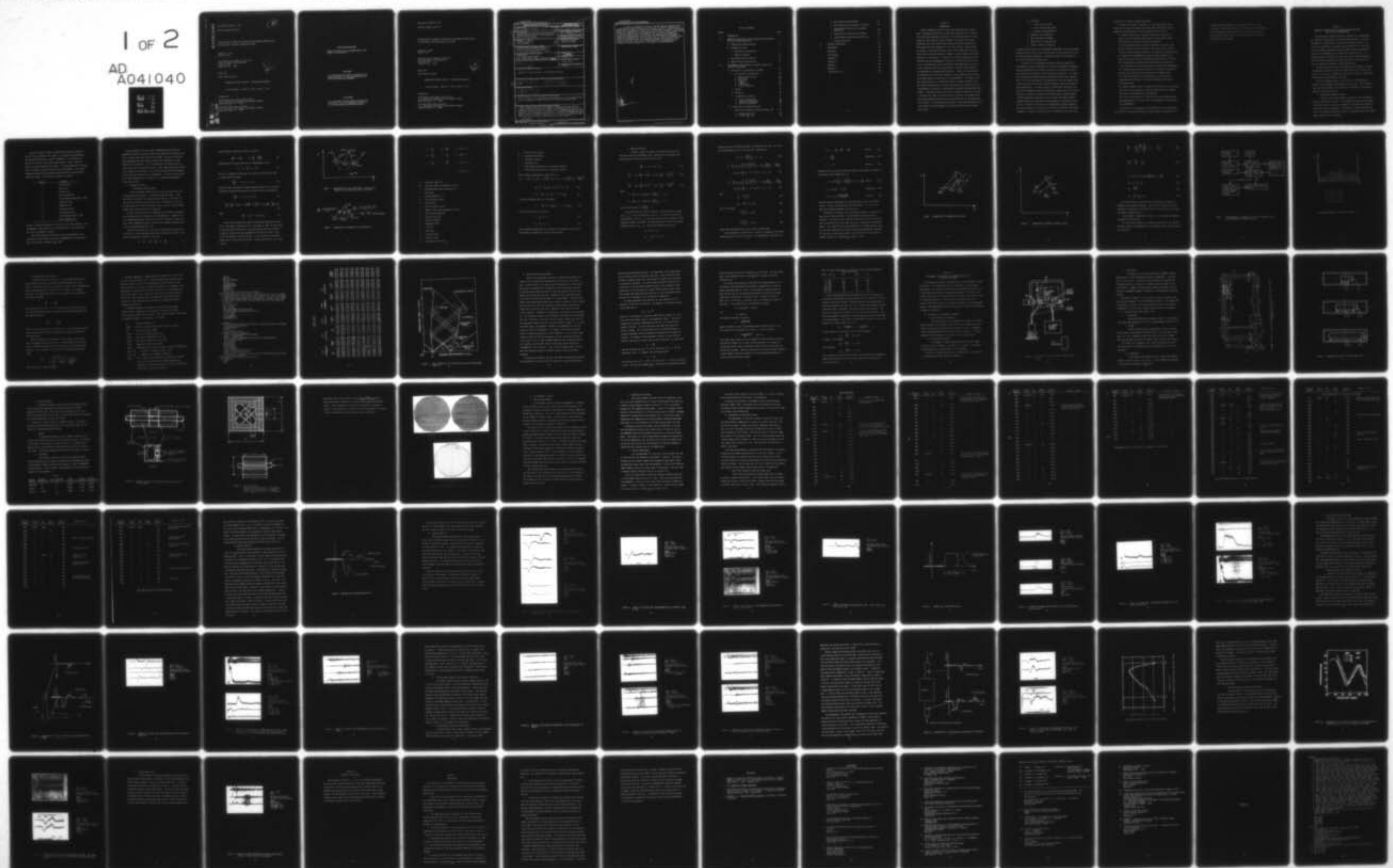

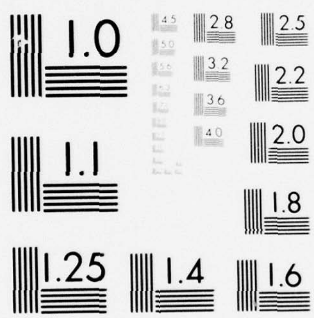

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UAH Research Report No. 199

Technical Report H-CR-77-9

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INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERISTIC OF HIGH ENERGY LASER GAS CIRCULATION SYSTEMS

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Huntsville, AL 35807

March 1977

Final Technical Report

APPROVED FOR PUBLIC RESEASE: DISTRIBUTION UNLIMITED

Period Covered: February 3, 1976 - March 31, 1977

Prepared for

High Energy Laser Systems Project Office
U. S. Army Missile Research and Development Command
Redstone Arsenal, AL 35809

Army High Energy Laser Laboratory
U. S. Army Missile Research and Development Command
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

As a parallel effort to the program initiated at the Army Missile Command to design and fabricate a small scale closed cycle circulator for repetitively pulsed electric discharge lasers at 200°K temperature and high pressures, this investigation was initiated to obtain the fundamental knowledge of fluid and thermal characteristics of the recirculating gas flow in the closed cycle circulator during the pulsed laser operation.

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In order to accomplish this goal, the UAH team has expended efforts in developing a subscale closed cycle laser gas circulator; constructing a muffler and reflectors and testing their effectiveness as acoustic and thermal attenuators; experimentally investigating the fluid and thermal characteristics of the recirculating flow associated with the pulsed wave propagation; studying the effectiveness of the blower and simulating heat exchangers; numerically simulating the recirculating flows for steady and unsteady cases as well as one-dimensional wave propagation models; and assisting in the design of the laser cavity to be incorporated with the Rocketdyne-built circulator from the standpoints of gas dynamics and thermodynamics.

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Chapter I

INTRODUCTION

Based on numerous studies of laser system applications in recent years, important applications of pulsed laser operation of all types of lasers have been apparently identified. The pulsed operation of a high energy gas laser presents special problems in the area of shock wave generation due to the sudden energy deposition and the interaction of these waves with other components of the laser system. These problems are present in both closed and open cycle laser systems and in all gas lasers such as electric discharge, chemical, and gas dynamic lasers when operated in a pulsed mode. In addition to shock wave generation, other transient gas flow thermodynamic problems are involved during the start up of a high energy gas laser system from a room temperature, zero flow initial condition until the establishment of "steady" flow conditions corresponding to sustained pulsed operation. These start up transients are characteristic of all high energy gas laser systems, both pulsed and CW and both open and closed cycle to varying degrees. The purpose of the work reported here is to investigate some of the major transient fluid and thermal characteristics of high energy pulsed laser operation and to study methods of reducing or eliminating the problems associated with such systems. The pulsed closed cycle electric discharge laser (EDL) was used as the basis for study in this work since it has most of the major fluid and thermal operating characteristics associated with all high energy gas laser systems. The following major technical issues were determined to be associated with the development of the pulsed closed cycle high energy laser system:

A. Transients

1. Start up recirculator
2. Start up laser input power
3. Acoustic waves/Attenuation

B. Boundary Layer Interaction

C. Heat Exchanger Performance

D. Medium Quality, Clearing Time

E. Plasma - Chemistry Stability

To answer some of these issues, fundamental knowledge of fluid and thermal characteristics of the recirculating gas flow in the closed cycle circulator during the laser operation is considered essential and necessary as one of basic engineering design tools.

To the best of our knowledge, experimental data and theoretical understanding directly attributable to the gain of fundamental knowledge and the substantiation of technical feasibility are lacking for the recirculating gas flow peculiar to the pulsed laser operation. At present, some of the major technical problems associated with the laser development of this kind are related to the questions of flow and thermal stabilities of the recirculating gas, plasma formation, pressure and thermal waves attenuations. For these reasons, a program was initiated at the Army Missile Command to design and fabricate a unique small scale closed cycle gas circulator for repetitively pulsed electric discharge lasers at 200°K temperature and high pressures in order that these potential problem areas can be identified and investigated at relatively low cost and risk. Results of this small scale program may, through comparison with other programs of larger scale circulators, contribute to the establishment of a realistic similarity law for the design of the full-scale

circulator at a saving of weight and volume.

As a part of the overall team effort in the program under the direction of the Army High Energy Laser Directorate, the UAH team has expended best-possible efforts in the following areas of concern.

(1) Design and fabricate a subscale closed cycle laser gas circulator to be incorporated with the Army's single pulsed E-beam controlled laser to conduct simulation experiments.

(2) Design and fabricate an acoustic attenuator (or muffler) and acoustic reflectors to be installed in the closed cycle circulator in order to study the wave attenuation and interaction characteristics.

(3) Develop an instrumentation system including capabilities to measure and record pressure, temperature and velocities of the flow.

(4) Experimentally investigate fluid and thermal characteristics of the recirculating flow associated with the pulsed wave propagation.

(5) Experimentally determine the effects of muffler and reflectors upon the wave attenuation of both acoustic and thermal types.

(6) Study experimentally the effectiveness of the blower and simulating heat exchangers as interacting elements with acoustic and thermal waves.

(7) Develop computer models to numerically simulate the recirculating gas flows in laser operation, including steady flow case, unsteady flow case, and one-dimensional wave analysis.

(8) Assist in the design of a laser cavity to be incorporated with the Rocketdyne-built circulator from the standpoints of gas dynamics and thermodynamics.

To the best of our knowledge, the experimental results reported here are the first to show the transient fluid and thermal characteristics of

a pulsed electric discharge in a functioning closed cycle gas circulator. These results should be of interest to those concerned with the design and operation of all types of pulsed gas lasers either closed or open cycle and including the electric discharge and chemical laser systems.

Chapter II

NUMERICAL SIMULATION OF THE RECIRCULATING AND UNSTEADY GAS FLOW IN LASER OPERATION

The experimental program described in Chapter III was supplemented by a numerical investigation of the fluid-thermal behavior of the gas. The numerical simulation work involved three computer programs. The first to be described is the steady state program which is a modification of a computer program which was available at UAH but needed modifications to accommodate the low temperature operating range. This computer program is designed to predict the steady state performance of the system which means that the pulsed operation of the system could only be simulated by assuming an average power input.

The second computer program to be described is designed to simulate the unsteady flow resulting from the sudden deposition of energy in the cavity. This program is capable of predicting the pressure, temperature, and velocity waves generated at the cavity.

The third computer program is the result of a one-dimensional analysis of the unsteady flow generated at the cavity. This program was used to provide estimates of the pressure and temperature environments expected in the cavity region.

A. Steady State Computer Program

The basic steady state computer program was first developed by AVCO for application to the MTU. This program was modified at UAH under a previous contract in order to accommodate a different heat exchanger design than originally employed in the program. Under the present contract, this program was modified further to simulate the 200 K gas system under consideration in this work.

The basic computer program is adequately described in Reference 1 and will not be covered in this report. A listing of the program with the current modifications is given in Appendix A. The results for a typical run is given in the tables which follow. Table 1 shows the input list used to generate the results. The system dimensions are those which correspond to the system being built by Rocketdyne. The computer program calculates the fluid-thermal characteristics at eleven points around the system. The stations are located as follows:

Station	Location
1	Cavity Entrance
2	Cavity Exit
3	Diffuser Exit
4	Constant Area Duct
5	Heat Exchanger (Room Temp.) Inlet
6	Compressor Inlet
7	Compressor Exit
8	Constant Area Duct
9	Constant Area Duct
10	Heat Exchanger (200 K) Inlet
11	Heat Exchanger Exit

The gas is loaded with energy at the cavity at the rate of 450 KW. This corresponds to about 900 J/ℓ on a continuous basis. The results for this run are presented in Table 2.

The results show that the pressure in the system doesn't vary a great deal and the thermal load can be accommodated on a steady state basis with the heat exchanger loads shown.

The gas properties for the range of temperature and pressure encountered by the gas in traveling about the system were investigated carefully to ensure that large errors were not made. No major difficulties were encountered since the pressure remains near atmospheric and the temperature is above 200 K. This investigation also revealed that the system could likely be operated at even a lower temperature without danger of CO_2 snowing out of the gas. This can be seen from the phase diagrams for the laser gas mixtures given in Appendix B. This work was performed by Mr. David Washington as an exercise in an advanced thermodynamics course taken at UAH.

B. Unsteady Flow Case

1. Theoretical Considerations

Fluid and thermal characteristics are to be studied along the recirculating gas flow path as a function of time and space. As the laser pulses, energy will be input into the laser gas. The effect of the pulse will be felt along the fluid loop. Disturbances in the form of shock waves will travel out from the cavity, as well as other thermal changes that travel with the fluid particles.

The basic equations which are combined into the governing equations are one-dimensional fluid mechanics and thermodynamics. Together with the accompanying boundary conditions and initial conditions, these equations form a mathematical model of the fluid and thermal characteristics of the recirculating laser gas flow.

Based on the principles of similitude, the pertinent quantities of the flow are in non-dimensionalized form and presented as follows. The continuity equation is written in the form

$$\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x} + \frac{\partial u}{\partial x} + \frac{u}{\alpha} \frac{\partial \alpha}{\partial x} = 0 \qquad (1)$$

and the dynamical equation of motion is given as

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = - \frac{1}{\rho} \frac{\partial P}{\partial x} - \frac{fu|u|}{2D} \tag{2}$$

Combining the first and second laws of thermodynamics gives

$$dS = C_v \frac{dT}{T} - R \frac{d\rho}{\rho} \tag{3}$$

The rate of change of entropy may be a function of position and time as shown implicitly below,

$$\frac{DS}{Dt} = f\ (x,\ t,\ a,\ u,\ S) \tag{4}$$

Normalizing and rearranging the above equations yield a set of partial differential equations governing the transient flow in one-dimension.

$$\frac{DS}{D\tau} = f\ (\xi,\ \tau,\ A,\ U,\ S) \tag{5}$$

$$\frac{\delta^{\pm}}{\delta\tau} \left(\frac{2}{\gamma-1} A \pm U\right) = - AU \frac{\partial \ell nd}{\partial \xi} + A \frac{\delta^{\pm} S}{\delta\tau} + (\gamma-1)\ A \frac{DS}{D\tau} - \frac{fL_o}{2D} U|U| \tag{6}$$

where

$$\frac{\delta^{\pm}}{\delta\tau} = \frac{\partial}{\partial\tau} + (U \pm A) \frac{\partial}{\partial \xi} \tag{7}$$

Since two of the governing partial differential equations are hyperbolic, they possess "characteristics," invariants in time. At each point in time and space, there are two invariants moving away from the point. A numerical solution can take advantage of this very fact and is thus called, the method of characteristics. It uses invariants from nearby known points to calculate other points. These characteristics are called P and Q.

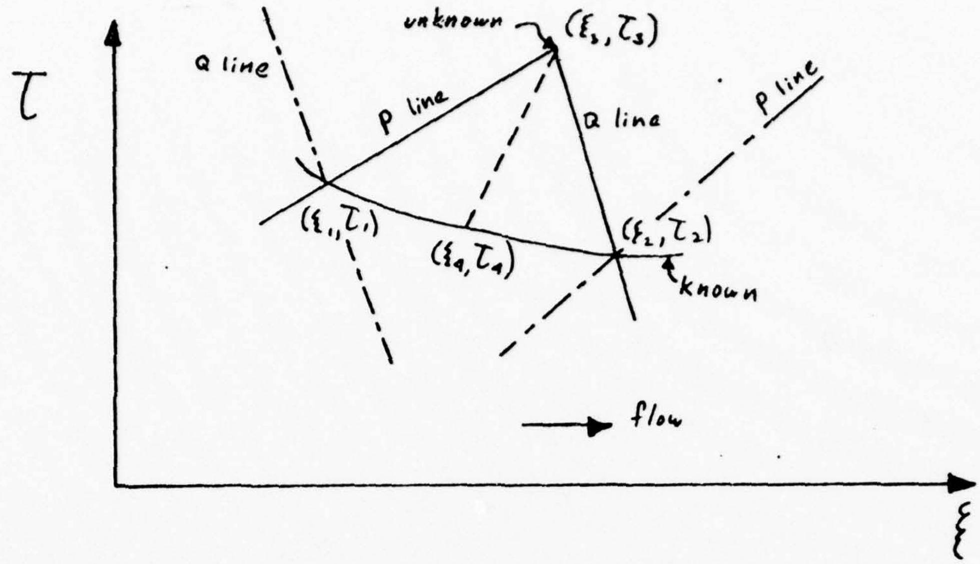


FIGURE 1. DETERMINATION OF FLOW CONDITIONS AT "LATER" OR AT "EARLIER" POINT FROM GIVEN INITIAL CONDITIONS.

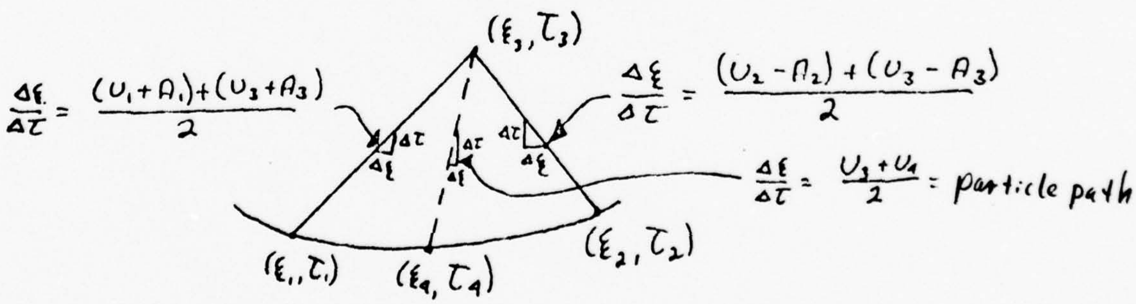


FIGURE 2. CHARACTERISTIC DIAGRAM FOR THE FLOW ANALYSIS.

$$A = \frac{a}{a_o} \qquad Q' = \frac{q}{\gamma RT} \qquad P = \frac{2}{\gamma-1} A + U$$

$$U = \frac{U}{a_o} \qquad \xi = \frac{x}{L_o} \qquad Q = \frac{2}{\gamma-1} A - U$$

$$S = \frac{s}{\gamma R} \qquad \tau = \frac{a_o t}{L_o} \qquad U = \frac{1}{2} (P - Q)$$

$$A = \frac{\gamma-1}{4} (P + Q)$$

L_o = reference length (ft)

a_o = reference speed of propagation (ft/sec)

x = one-dimensional space coordinate (ft)

t = time (sec)

s = entropy (Btu/lbm - 'R)

u = flow velocity (ft/sec)

R = gas constant

γ = ratio os specific heats

a = speed of sonic wave propagation (ft/sec)

q = heat transfer (Btu/lbm)

p = pressure (lb_f/ft^2)

ρ = density ($slug/ft^3$)

T = temperature (^oR)

a = $(\gamma R T)^{1/2}$

α = area ratio

f = friction factor

A = speed of sound

U = fluid particle velocity

S = fluid particle entropy

Q' = fluid particle heating

ξ = coordinate distance

τ = coordinate time

P = right moving characteristic of governing equation

Q = left moving characteristic of governing equation

Their respective mathematical definitions are:

Let $I = \frac{2}{\gamma-1} A \pm U$; $N_A = - AU \frac{\partial \ell n \alpha}{\partial t}$; $N_B = A$; $N_C = (\partial - DA \frac{DS}{D\tau})$; $N_D = \frac{f L_o U|U|}{2D}$

$$\frac{\delta}{\delta\tau} (I) = N_A + N_B \frac{\delta}{\delta\tau} (S) + N_C + N_D \qquad (8)$$

$$\delta (I) = (N_A + N_C + N_D) \delta\tau + \delta (S) N_B \qquad (9)$$

In finite difference form, Eq. (9) becomes

$$\Delta I = (N_A + N_C + N_D)_{ave} \Delta \tau + \Delta S (N_B)_{ave} \qquad (10)$$

Let the characteristics be given as

$$P = \frac{2}{\gamma-1} A + U \qquad (11)$$

$$Q = \frac{2}{\gamma-1} A - U \qquad (12)$$

Now the governing equations can be applied to the numerical solution of the unsteady one-dimensional flow in the circulator.

2. Numerical Analysis

To apply a numerical scheme, the governing equations are written in the finite difference form. Equation (5) then becomes (13) and Equation (6) produces Equations (14) and (15).

$$\frac{DS}{D\tau} = \sigma\ (\xi,\ \tau,\ A,\ U,\ S) \tag{13}$$

$$\frac{\delta_+ P}{\delta\tau} = -\ AU\ \frac{\partial \ell n \alpha}{\partial \xi} + A\ \frac{\delta_+ S}{\delta\tau} + (\gamma - 1)\ A\ \frac{DS}{D\tau} - f\ \frac{L_o\ U|U|}{2D} \tag{14}$$

$$\frac{\delta_- Q}{\delta\tau} = -\ AU\ \frac{\partial \ell n \alpha}{\partial \xi} + A\ \frac{\delta_- S}{\delta\tau} + (\gamma - 1)\ A\ \frac{DS}{D\tau} - f\ \frac{L_o\ U|U|}{2D} \tag{15}$$

where

$$P = \frac{2}{\gamma - 1}\ A + U \quad \text{moving at} \quad \left(\frac{d\xi}{d\tau}\right)_P = U + A$$

$$Q = \frac{2}{\gamma - 1}\ A - U \quad \text{moving at} \quad \left(\frac{d\xi}{d\tau}\right)_Q = U - A$$

and a particle moves at $\left(\frac{d\xi}{d\tau}\right)_S = U.$

Two known points are used to calculate a third new point, located at $(\xi_3,\ \tau_3)$. The P characteristic from $(\xi_1,\ \tau_1)$ intersects with the Q characteristic from $(\xi_2,\ \tau_2)$, since the slopes of the invariants, called Riemann variables, are known. By knowing that the P and Q are constant, they must exist at $(\xi_3,\ \tau_3)$. Now we can calculate U_3 and A_3 by

$$U_3 = \frac{1}{2}\ (P - Q)$$

$$A_3 = \frac{\gamma - 1}{4}\ (P + Q).$$

Iteration of this principle continues as follows with Eq. (16), (17), and (18) representing Eq. (13), (14), and (15), respectively.

$$S_3 = S_4 + \left(\frac{DS}{D\tau}\right)_{43} (\tau_3 - \tau_4) \tag{16}$$

$$P_3 = \left[- A_{13}\, U_{13} \left(\frac{\partial\ \ell n\ (D_3/D_1)}{\xi_3 - \xi_1}\right) + (\gamma-1)\, A_{13} \left(\frac{DS}{D\tau}\right)_{13} - \frac{f_{13}L_o}{2\, D_{13}} U_{13}\, |U_{13}|\right] (\tau_3 - \tau_1) + A_{13}\,(S_3 - S_1) + P_1 \tag{17}$$

$$Q_3 = \left[- A_{23}\, U_{23} \left(\frac{\partial\ \ell n\ (D_3/D_2)}{\xi_3 - \xi_2}\right) + (\gamma-1)\, A_{23} \left(\frac{DS}{D\tau}\right)_{23} - \frac{f_{23}L_o}{2\, D_{23}} U_{23}\, |U_{23}|\right] (\tau_3 - \tau_2) + A_{23}\,(S_3 - S_2) + Q_2 \tag{18}$$

Then,

$$U_3 = \frac{P_3 - Q_3}{2} \tag{19}$$

$$A_3' = \frac{\gamma-1}{4} (P_3 + Q_3) \tag{20}$$

Test for iteration:

$$\frac{U_3' - U_3}{U_3'} \leq 0.001 \tag{21}$$

$$\frac{A_3' - A_3}{A_3'} \leq 0.001 \tag{22}$$

where the primed quantities are the newly calculated ones.

Once the method of characteristics solution is completed, the thermodynamic quantities can be calculated. The thermodynamics equations are:

$$d\,\ell n\,\rho = \frac{2}{\gamma-1}\frac{da}{a} - \frac{ds}{R} \qquad \text{density} \qquad (23)$$

$$T = \frac{a^2}{\gamma R g_c} \qquad \text{temperature} \qquad (24)$$

$$P = \rho\, R\, T \qquad \text{pressure} \qquad (25)$$

Equations (23) to (25) are modified according to the numerical scheme of calculation of the unknown point as

$$\rho_3 = \rho_1 \exp\left[\frac{2}{\gamma-1}\ \ell n\left(\frac{A_3}{A_1}\right) - \gamma\,(S_3 - S_1)\right] \qquad \text{density} \qquad (26)$$

$$T_3 = (A_3\, a_o)^2\ /\ (\gamma\, Rg_c) \qquad \text{temperature} \qquad (27)$$

$$P_3 = \rho_3\, R\, T_3\ \left(\frac{32.17\ \text{lbm}}{1\ \text{slug}}\right) \qquad \text{pressure} \qquad (28)$$

Now the solution scheme moves on to two more known points to calculate a third. Finally, an entire new line is calculated. It, in turn, is then used to generate another line, and so on.

The method of characteristics only breaks down when it must cross a shock wave or contact surface. Any discontinuity requires special attention. The solution must find the intersection of the discontinuity with the characteristics and "jump" across to a new point to continue as before. This "jump" across the characteristics is accomplished by using Eqs. (29) and (30) which are derived from the Rankine-Hugoniot relations for the case of shock waves and Eqs. (31) through (34) for the case of contact surfaces as illustrated in Figures 3 and 4.

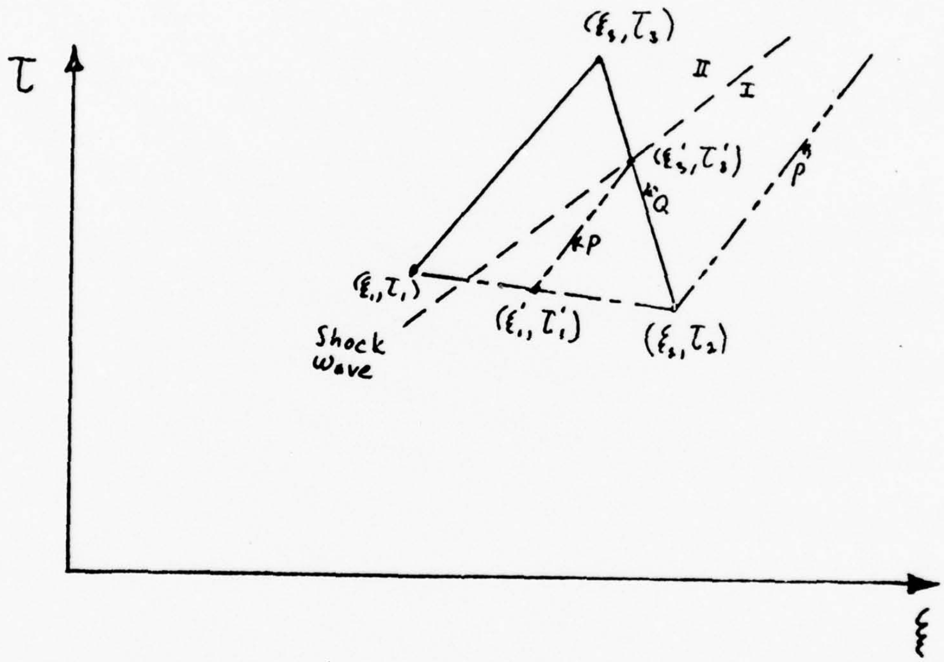


FIGURE 3. CHARACTERISTIC DIAGRAM FOR SHOCK WAVE.

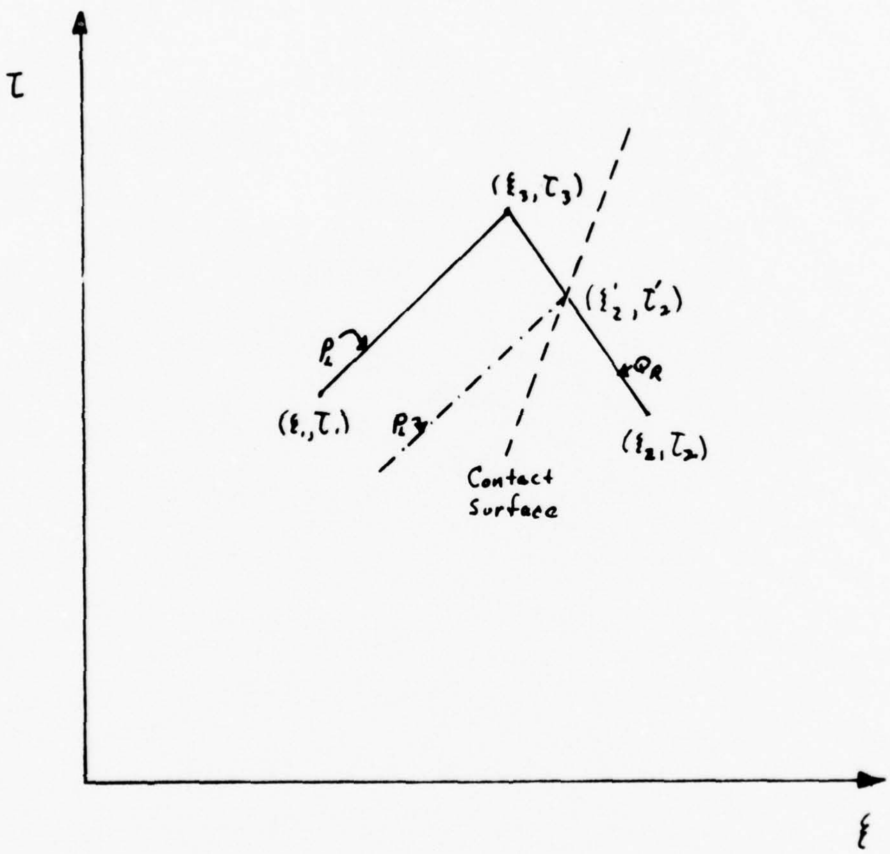


FIGURE 4. CHARACTERISTIC DIAGRAM OF CONTACT SURFACE.

$$\frac{\rho_{II}}{\rho_I} = \frac{1 + \frac{\gamma+1}{\gamma-1} \frac{\rho_{II}}{\rho_I}}{\frac{\gamma+1}{\gamma-1} + \frac{P_{II}}{P_I}} = \frac{U_I}{U_{II}} \tag{29}$$

$$\frac{T_{II}}{T_I} = \frac{P_{II}}{P_I} \quad \frac{\rho_I}{\rho_{II}} \tag{30}$$

$$Q_L = Q_R + (P_L + Q_R) \tanh \left[\frac{\gamma-1}{4} (S_L - S_R)\right] \tag{31}$$

$$P_R = P_L + Q_R - Q_L \tag{32}$$

$$U_2' = \frac{P_R - Q_L}{2} \tag{33}$$

$$A_2' = \frac{\gamma-1}{4} (P_R + Q_L) \tag{34}$$

Each shock wave and interface must be continually followed and updated as the solution progresses. The "cut off" known point must be replaced by a new point on the other side of a discontinuity to continue the method of characteristics.

A flow diagram is presented in Figure 5 to illustrate the numerical procedure for the solution.

The final results should be a location-time history of the velocity, pressure, density, and temperature of the unsteady flow in the circulator as shown below.

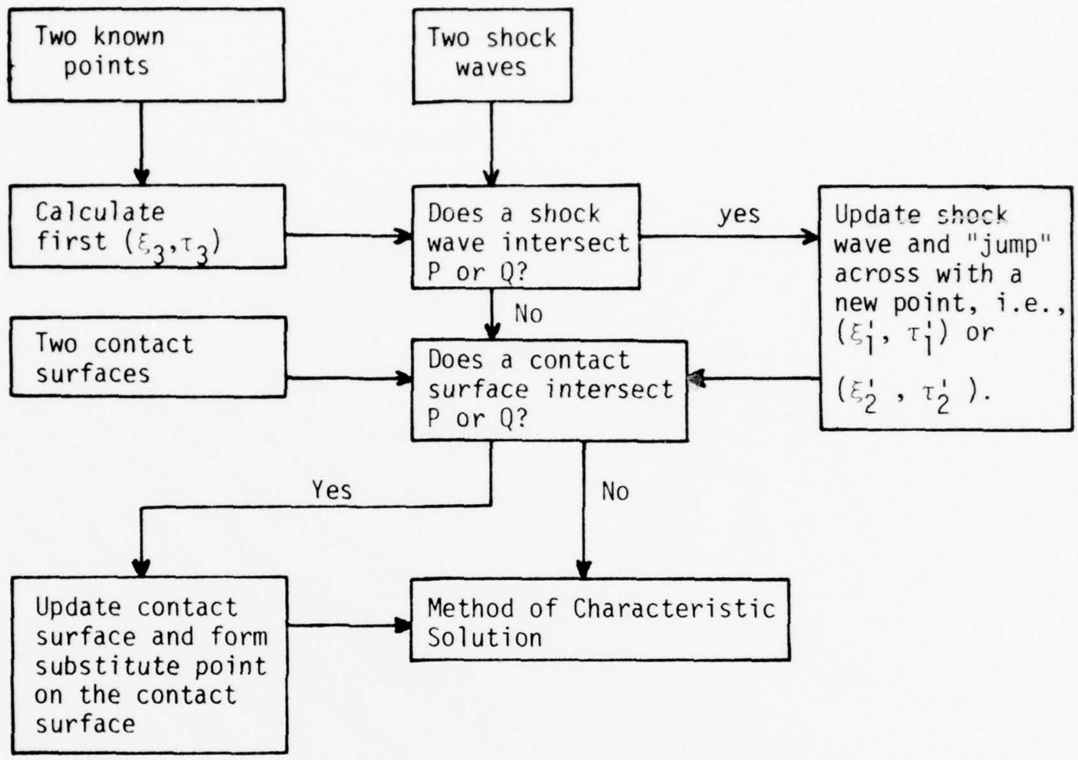
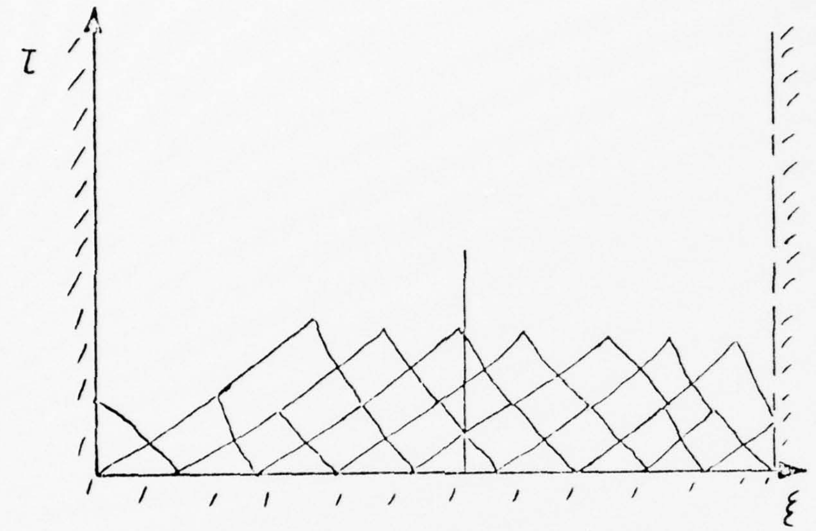


FIGURE 5. FLOW DIAGRAM OF THE NUMERICAL SOLUTION OF UNSTEADY FLOWS USING THE METHOD OF CHARACTERISTICS.



$$P = P(\xi,\tau) = P(x,t)$$

$$\rho = \rho(\xi,\tau) = \rho(x,t)$$

$$T = T(\xi,\tau) = T(x,t)$$

$$U = U(\xi,\tau) = U(x,t)$$

The computer program is attached as Appendix C.

C. One-Dimensional Wave Analysis

Following the work of Foa (Ref. 2), a one-dimensional analysis was performed on the waves produced by the energy deposition in the cavity. The initial conditions are assumed to result from an instantaneous-constant-volume heating of a region of gas of length L in a constant area duct. The energy deposited goes into heating the gas according to the following equation

$$\dot{Q} = C_v \frac{dT}{dt}$$

Using the perfect gas law, $p = \rho RT$, and using the fact that the initial and final density are the same, we obtain the following relationship for the change in pressure

$$\frac{\Delta P}{P_o} \approx \frac{q}{C_v T_o}$$

where q is the energy per unit mass deposited. Thus, the equations above can be used to find the initial temperature and pressures produced by the energy pulse.

The over pressure at the boundaries of the region cause a shock wave to propagate away from the cavity. The Mach number of this shock wave is determined uniquely from the pressure ratio using normal shock relations. For a pressure ratio of P_1/P_o, the following relationship holds

$$\frac{P_1}{P_o} = \frac{2\,k\,M_s^2 - k + 1}{(k+1)\left[1 - \frac{k-1}{k+1}\left(M_s - \frac{1}{M_s}\right)\right]^{\frac{2k}{k-1}}}$$

The value of M_s is found numerically.

The wave propagation is shown sketched in Figure 6 for flow from left to right. The shock waves travel in both directions away from the cavity. Behind the shock is a hot-cold interface which initially moves in the same directions as the shocks. Behind the interface is an expansion fan which moves in the opposite direction of the shocks. The expansion fans cross at the center of the cavity (for no flow case) and then interact with the hot-cold interface which was generated at the opposite end of the cavity. This intereation has the effect of stopping the outward movement of the hot gas.

A computer program was developed to calculate the shock speed, pressure ratios, temperatures, and expansion of the hot gas region. This program is given on the next page. The results are given in the table following the program. The notation is as follows:

QV	=	the pulse energy in J/ℓ
U3MU1	=	velocity in region 3 minus the velocity in region 1
FM	=	M_s, the shock Mach number
P1VP0	=	the initial pressure ratio p_1/P_0
T1VT0	=	the initial temperature ratio T_1/T_0
P3VP0	=	the pressure ratio across the shock
T3VT0	=	temperature ratio across shock
T2VT0	=	temperature of hot gas with respect to initial temperature
P0,P1, etc.	=	pressure in respective region, N/m^2
T0,T1, etc.	=	temperature in respective region, K.
EXPAN	=	$\frac{\Delta X}{L}$, a point at which the hot-cold interface is intersected by the expansion wave, thereby stopping the expansion of the hot gas region. The value is normalized with respect to the cavity length, L.

```
      QV=0.0
      P0=14.7
      ACK = 0.000001
      T0=200.
      RHO0=1.7658
      CSUBV=718.285
      GAMMA=1.4
      WAT=22.4
      FAC = 1.15
      WRITE(6,100) ACK,RHO0,CSUBV,GAMMA,WAT
  100 FORMAT(1H1,59X,'LASER SHOCK',/,60X,'-----------',/,/,/,/,34X,
     1 'ACK',12X,'RHO0',10X,'CSUBV',10X,'GAMMA',11X,'WAT',/,/,26X,
     2 5E15.6,/,/,/,/,/,/,12X,'QV',11X,'U3MU1',12X,'FM',11X,'P1VP0',
     3 10X,'T1VT0',10X,'P3VP0',10X,'T3VT0',10X,'T2VT0',/,12X,'P0',
     4 12X,'T0',14X,'P1',12X,'T1',13X,'P3',13X,'T3',13X,'T2',12X,
     5 'EXPAN')
      DO 20 J=1,100
      QV = J*50.
      QF = QV*FAC
      A0=SQRT(GAMMA*8314.34*T0/WAT)
      P1VP0=QF*1000./(RHO0*CSUBV*T0)+1.0
      T1VT0=P1VP0
      TG=2.*GAMMA
      GM1=GAMMA-1.0
      GP1=GAMMA+1.0

      FM=1.0
    9 FMS=SQRT(GM1/TG+(GP1/TG)*T1VT0*(1.0-(GM1/GP1)*SQRT(1./T1VT0)*
     1 (FM-1./FM))**(TG/GM1))
      FCH=ABS(FMS-FM)
      FM=FMS
      IF(FCH-ACK)10,10,9
   10 P3VP0=(TG*FM*FM-GM1)/GP1
      T1VT2 = (P1VP0/P3VP0)**(GM1/GAMMA)
      T2VT0 = P1VP0/T1VT2
      T3VT0 = P3VP0*(1.0+(GM1/GP1)*P3VP0)/(P3VP0+GM1/GP1)
      A1 = A0*SQRT(P1VP0)
      T3=T3VT0*T0
      P3=P3VP0*P0
      P1=T1VT0*P0
      T1=T1VT0*T0
      T2 = T2VT0*T0
      U3MU1=(2.*A0/GP1)*(FM-1./FM)
      EXPAN = A1/(A1-U3MU1)-1.0
      WRITE(6,101) QV,U3MU1,FM,P1VP0,T1VT0,P3VP0,T3VT0,T2VT0,P0,T0,
     1 P1,T1,P3,T3,T2,EXPAN
  101 FORMAT(1H0,2X,8E15.6,/,3X,8E15.6)
   20 CONTINUE
      STOP
      END
```

LASER SHOCK

ACK	RHOO	CSUBV	GAMMA	WAT
.100000-05	.176580+01	.718285+03	.140000+01	.224000+02

QV P0	U3MU1 T0	FM P1	P1VP0 T1	T1VT0 P3	P3VP0 T3	T3VT0 T2	T2VT0 EXPAN
.500000+02	.247414+02	.104711+01	.122667+01	.122667+01	.111251+01	.103097+01	.119291+01
.147000+02	.200000+03	.180321+02	.245335+03	.163538+02	.206193+03	.238582+03	.744521-01
.100000+03	.471752+02	.109165+01	.145335+01	.145335+01	.122364+01	.105962+01	.138364+01
.147000+02	.200000+03	.213642+02	.290669+03	.179876+02	.211923+03	.276727+03	.138153+00
.150000+03	.677674+02	.113405+01	.168002+01	.168002+01	.133374+01	.108652+01	.157280+01
.147000+02	.200000+03	.246963+02	.336004+03	.196060+02	.217303+03	.314560+03	.193572+00
.200000+03	.868519+02	.117462+01	.190669+01	.190669+01	.144303+01	.111207+01	.176079+01
.147000+02	.200000+03	.280284+02	.381338+03	.212126+02	.222413+03	.352158+03	.242399+00
.250000+03	.104677+03	.121362+01	.213336+01	.213336+01	.155169+01	.113654+01	.194788+01
.147000+02	.200000+03	.313605+02	.426673+03	.228098+02	.227308+03	.389576+03	.285852+00
.300000+03	.121431+03	.125122+01	.236004+01	.236004+01	.165982+01	.116014+01	.213425+01
.147000+02	.200000+03	.346925+02	.472007+03	.243993+02	.232029+03	.426850+03	.324836+00
.350000+03	.137264+03	.128759+01	.258671+01	.258671+01	.176753+01	.118303+01	.232004+01
.147000+02	.200000+03	.380246+02	.517342+03	.259826+02	.236607+03	.464008+03	.360058+00
.400000+03	.152294+03	.132284+01	.281338+01	.281338+01	.187488+01	.120533+01	.250536+01
.147000+02	.200000+03	.413567+02	.562677+03	.275607+02	.241067+03	.501072+03	.392067+00
.450000+03	.166617+03	.135708+01	.304006+01	.304006+01	.198194+01	.122713+01	.269029+01
.147000+02	.200000+03	.446888+02	.608011+03	.291345+02	.245426+03	.538057+03	.421307+00

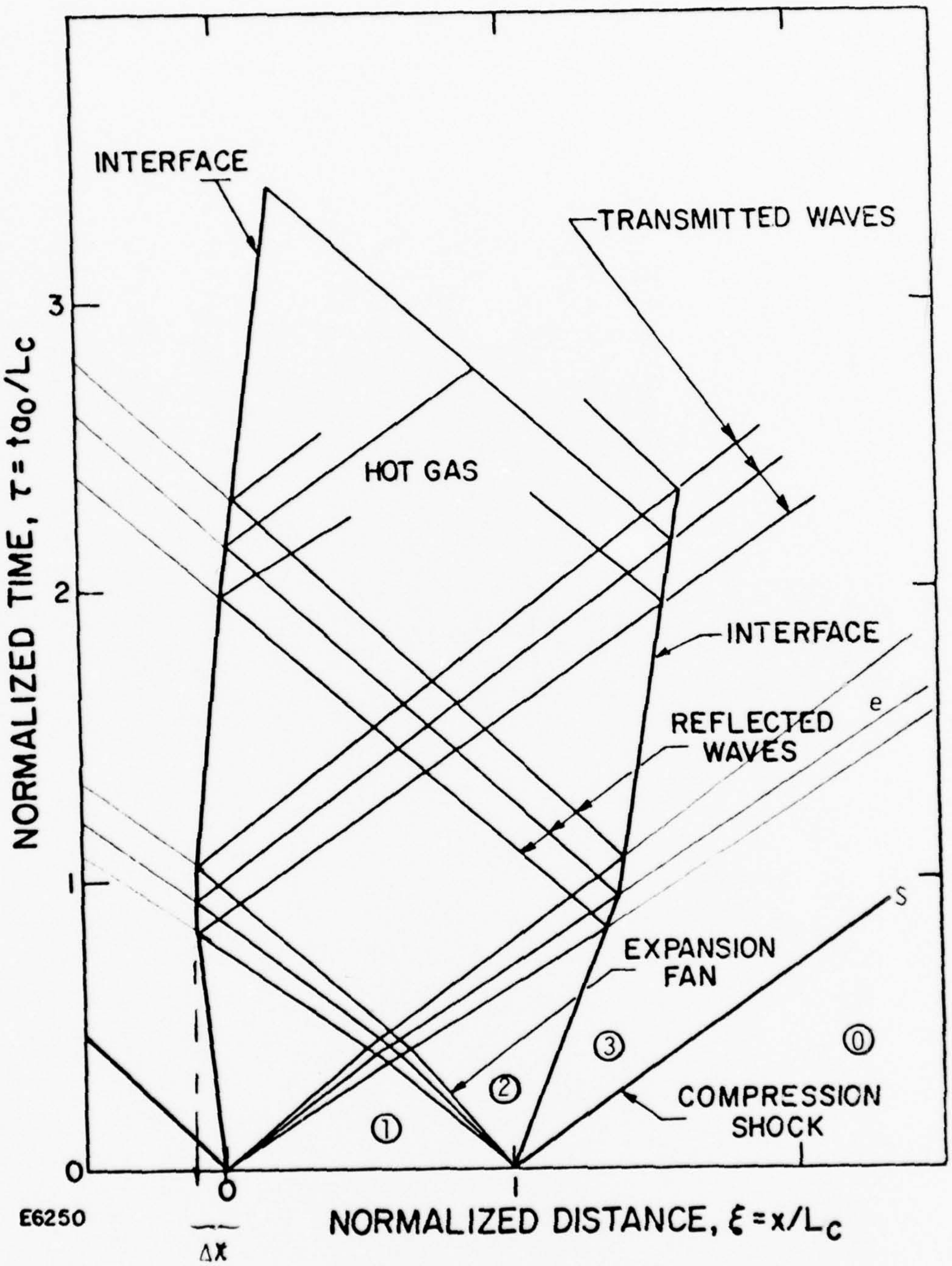


FIGURE 6. WAVE PROPAGATION AND INTERACTION BASED ON ONE-DIMENSIONAL ANALYSIS.[3]

D. Muffler Design Considerations

Mufflers are described as devices to reduce the transmission of sound while at the same time allowing the free flow of gas in a duct or pipe. An ideal muffler for a pulsed laser system would be a device which would reduce considerably the transmission of the shock waves produced by the high energy deposition while at the same time allow for the free unobstructed flow of the laser gas. Mufflers of this type employ holes in the side of the duct which connect to a closed region. Through proper design, the pressure wave energy can be directed from the gas flow, through the side holes, and into the dissipation region without disturbing the steady flow of the gas in the duct. Mufflers of this type are called volume resonators. Parameters of importance in the design of such mufflers are: the frequency of waves to be attenuated, the volume of the resonator, the size of the holes in the duct, and the length (if other than zero) of the tubes which connect the holes with the resonator volume.[4] As is typical of muffler design, the geometric parameters are dependent upon the frequency of sound to be attenuated. For example, the required resonator volume is inversely proportional to the frequency. For this reason, high frequency sound can often be attenuated by simply making the duct walls out of acoustic tile or other commonly employed sound proofing materials. Low frequency pressure waves require volumes much larger than can be accommodated in wall coverings. Thus, for low frequency sound, the duct must have openings along the side which connect to the large volume resonator.

As discussed in previous sections, the ideal one-dimensional pressure wave generated by the laser pulse will appear as a square wave pressure

pulse traveling through the system. The square wave can be approximated by an infinite series of sine and cosine waves. Thus, the muffler must be able to attenuate waves over a wide band in frequency to be effective in pulsed laser operation. In order to make the muffler effective over a wide band, it was decided to couple the duct to the resonator volume through the use of horn amplifiers rather than the tubes normally used. The straight tube design would be effective at only one frequency while the horn has the potential for a wide band of frequencies.

The ideal exponential horn amplifier has the characteristic of a high pass filter with no reflection. The geometry of the area variation of the ideal horn is

$$A(x) = A_o e^{Bx}$$

where $A(x)$ is the area at a position x away from the throat, A_o is the area at the horn throat, and B is the exponential factor. The cut off frequency of the horn is determined by the value of B and the total length of the horn. For zero reflection, the ideal horn must be infinite in length. For a finite length horn, the reflected energy is frequency dependent, with the reflection increasing for the lower frequencies. For example, if the exponential factor B is such that the radius of the horn of circular cross section at the exit, r_e, were to be

$$r_e = \frac{2}{B}$$

then the reflection at $\omega/B = 4 \times 10^4$ is 10% but at $\omega/B = 2 \times 10^4$ the reflection is 30%. If, however, the relationship were

$$r_e = \frac{1}{B}$$

the reflection at $\omega/B = 4 \times 10^4$ is 25% and at $\omega/B = 2 \times 10^4$ the reflection is 55%. Thus, the horn geometry for a finite horn has considerable effect

on the filtering and reflection capabilities of the horn. The table below gives a more complete picture of the geometric influence on the horn characteristics.

For pulsed laser operation at 200 pulses per second maximum, all of the energy in the resulting pressure waves is expected to be in the frequency range above 200 Hz. Thus, a horn designed for 200 Hz should remove from the flow all the pressure wave energy in the 200 Hz and above range since a horn acts as a high pass filter. Consider a design in which $\omega/B = 4 \times 10^4$ and $r_e = 2/B$ which gives a 5% reflection as seen in the table. If this design were to be effective at 200 Hz,

$$B = 1257/4\text{x}10^4 \approx .037 \text{ cm}^{-1}$$

and

$$r_e = 63.66 \text{ cm}$$

The length of the horn is given by

$$L = \frac{\ell n \left(Ae/Ao \right)}{B}$$

where the length is seen to be dependent upon the throat area Ao. Take the throat area to correspond to a radius of 1 cm and we obtain

$$L = \frac{\ell n \ (63.66/1)^2}{.03} = 276.9 \text{ cm}$$

which shows that a horn 9 ft long is needed to be 95% effective at 200 Hz. An effective length of 9 ft could likely be obtained in a folded horn design which would occupy a reasonable volume and thus be applicable for pulsed laser systems. Therefore, theoretically, the horn-coupled-resonator muffler appears to have the potential for the wide band performance required in the pulsed laser systems.

Table of Percent Reflection as a Function of ω/B for Three Exponential Horn Shape Factors

cm/sec ω/B \ r_e	1/B	4/3B	2/B
2×10^4	55%	40%	33%
4×10^4	25%	12%	5%
6×10^4	15%	8%	3%
8×10^4	11%	5%	2%
16×10^4	6%	3%	1%
24×10^4	4%	2%	0%
32×10^4	3%	1%	0%

A horn-coupled-resonator was designed and built for the purpose of investigating experimentally the performance of such a muffler in the UAH subscale recirculation system. Available materials were employed which limited the length of the horn to 6.5 cm. The horn was designed to be two dimensional with a rectangular cross section rather than circular. The width at the opening was limited to 11.5 cm plus the throat width. Thus, with these geometric constraints, the horn expansion factor was restricted to be approximately .3 for values of throat width of about 1 to 2 cm. For example, for a throat width of 1.5 cm,

$$B = \frac{\ell n \; Ae/Ao}{L} = \frac{\ell n \; (13/1.5)}{6.5} = .33$$

For this value of B, the value of ω/B for 200 Hz becomes,

$$\frac{\omega}{B} = \frac{1252}{.3} = .42 \times 10^4 \quad ,$$

at 1000 Hz, this becomes

$$\frac{\omega}{B} = \frac{6283}{.3} = 2.1 \times 10^4$$

and at 2000 Hz,

$$\frac{\omega}{B} = \frac{12570}{.3} = 4.2 \times 10^4$$

Thus, we expect the horn described above to be effective for frequencies above 1000 Hz based on the ω/B ratio and reference to the table on percent reflection.

Chapter III

EXPERIMENTAL INVESTIGATION OF SUBSCALE CLOSED CYCLE LASER GAS CIRCULATOR

A recirculation system was designed for use with the MICOM S^3 single pulse laser. This system was built for the purpose of investigating experimentally the transient flow and heating problems characteristic of a high energy laser system. The equipment employed in this work is described in Section A of the following which includes a description of the recirculation apparatus, a muffler used in wave attenuation tests, acoustic reflectors, and the instrumentation employed in the experimental program. The experimental data collected by this system will be described in general in Section B.

A. Description of Experimental Equipment

1. Recirculating Flow Apparatus

The recirculation system consisted of a blower, PVC piping, mounting flanges for attachment to the S^3 laser, an E-beam mask, and a plastic structure which was mounted inside the S^3 cavity. A schematic of the system attached to the S^3 laser is given in Figure 7. The flow through the cavity region is from right to left in that figure.

a. Blower Specifications

The blower is a Dayton Model 4C108 with a 10 5/8" wheel. The inlet is 6½" in diameter. The outlet is 2½" square. The outside of the blower casing is approximately 13" in diameter.

The motor is connected directly to the blower wheel. The motor is a 1 hp Dayton Model 6K232 operated at 3450 rpm.

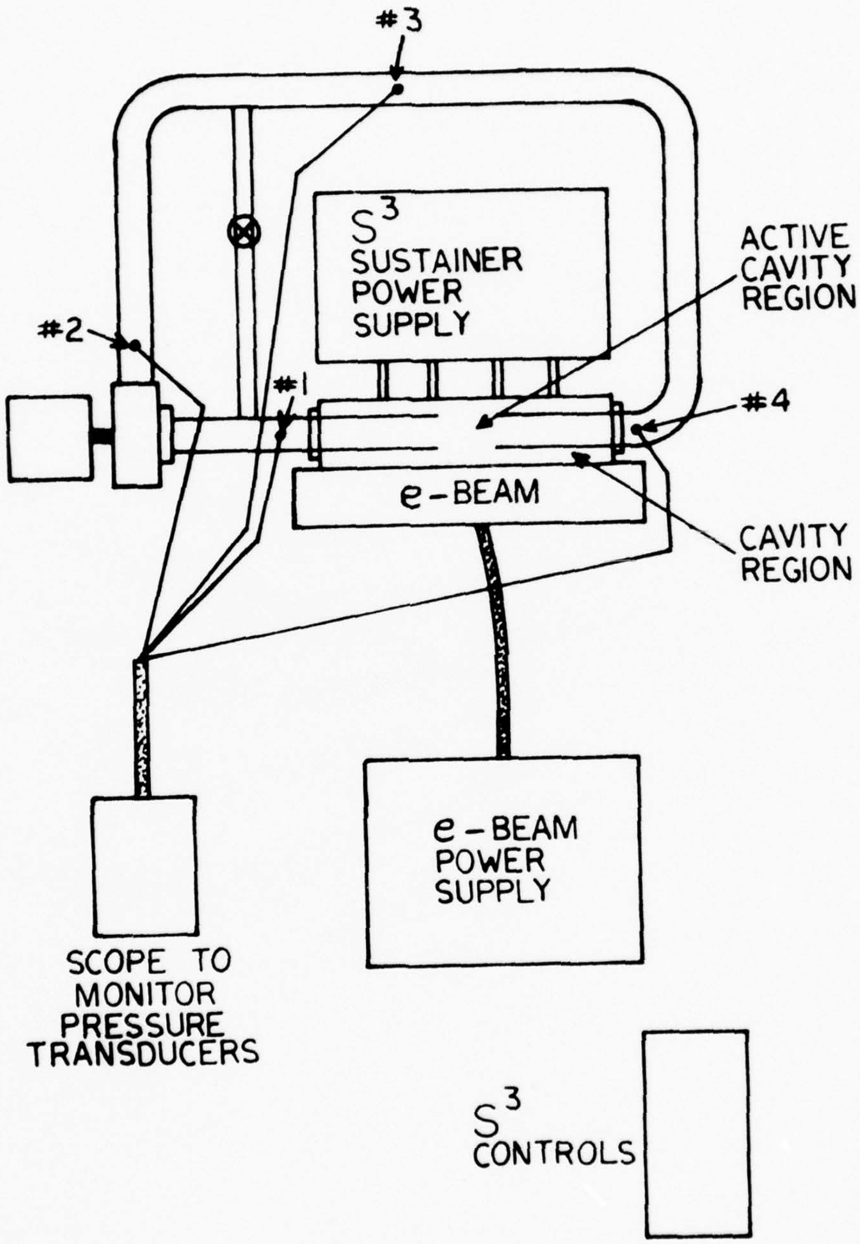


FIGURE 7. TOP VIEW OF PVC SUBSCALE MODEL ATTACHED TO THE S^3 LASER.

b. PVC Piping

The majority of the piping consisted of 3109662 "Certain-Teed Plastics" 4" PVC 1120 Schedule 40 220 psi ASTMD-2665. This pipe has 4" ID and 4½" OD. The 90^{0} turns were achieved using standard PVC fittings which have a 4" radius of curvature along the center line of the 90^{0} bend. A number of couplings were employed throughout the path length to accommodate assembly, disassembly, and modification during the testing.

Also shown in Figure 7 is a cross-over or by-pass pipe with valve. This pipe was J24G264 1" PVC 1120 Schedule 80 630 psi at 73^{0}F ASTMD 1785. The pipe was 1" ID and 1¼" OD and was attached to the 4" PVC through a standard 4" to 2" tee with a reducer used to bring the size down to 1". A 1" gate valve was used in the 1" line.

c. Dimensions

The piping dimensions are shown on Figure 8 in centimeters. Total path length around the 4" circuit is approximately 1140 cm (37 ft.)

d. Flanges

Special flanges had to be constructed in order to attach the PVC pipe to the blower and to the S^3 laser. For the blower attachment, a 6" to 4" reducer was used on the inlet side and an aluminum piece was machined to go from the square to the circular cross-section.

The flanges for attachment to the S^3 were constructed from aluminum consisting of 4½" diameter holes with suitable bolt circle and o-ring groove.

e. E-beam Masks

The purpose of the E-beam mask is to contain the E-beam to within a specified region of the cavity. Figure 9 shows the dimensions of the three masks employed in this work.

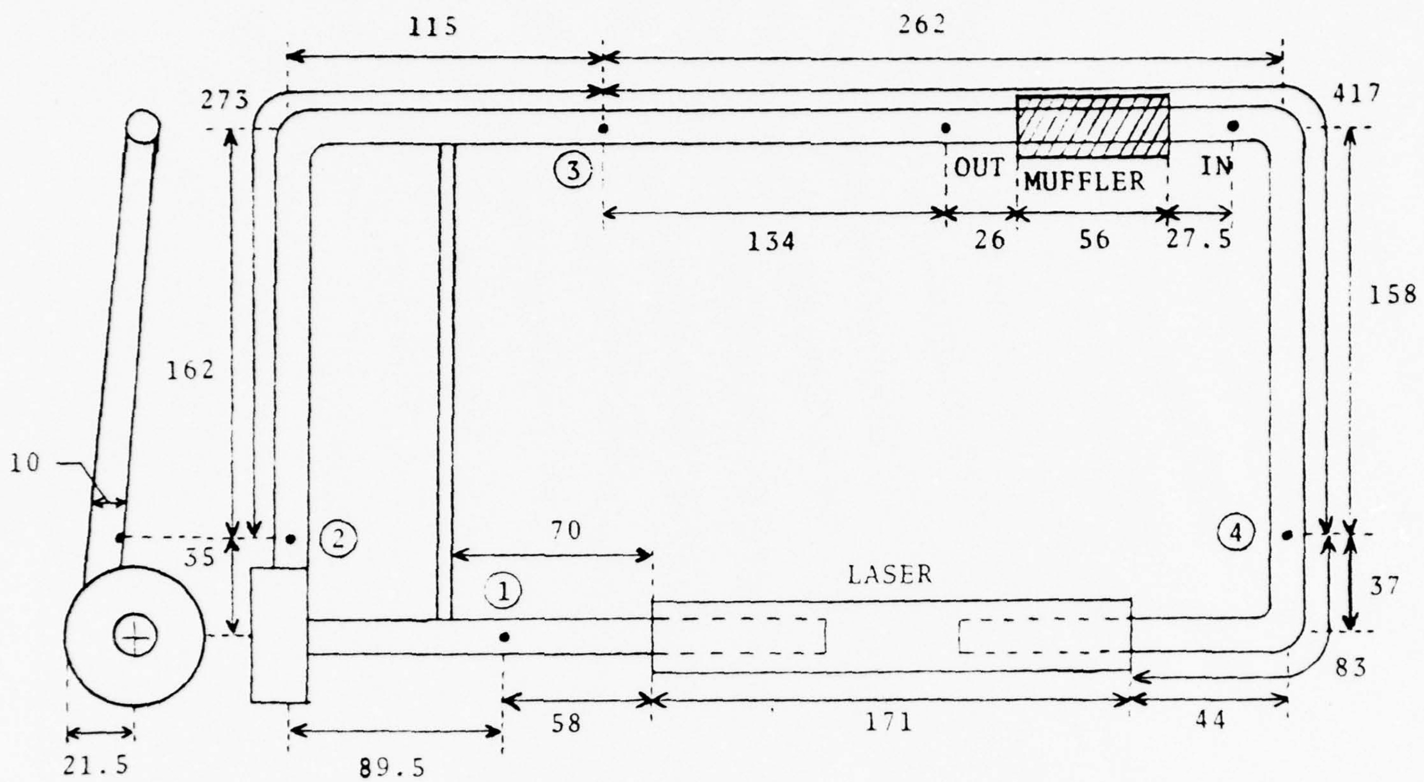


FIGURE 8. PROBE LOCATION MEASUREMENTS ON PVC MODEL WITH MUFFLER ADDED
(Dimensions in cm)

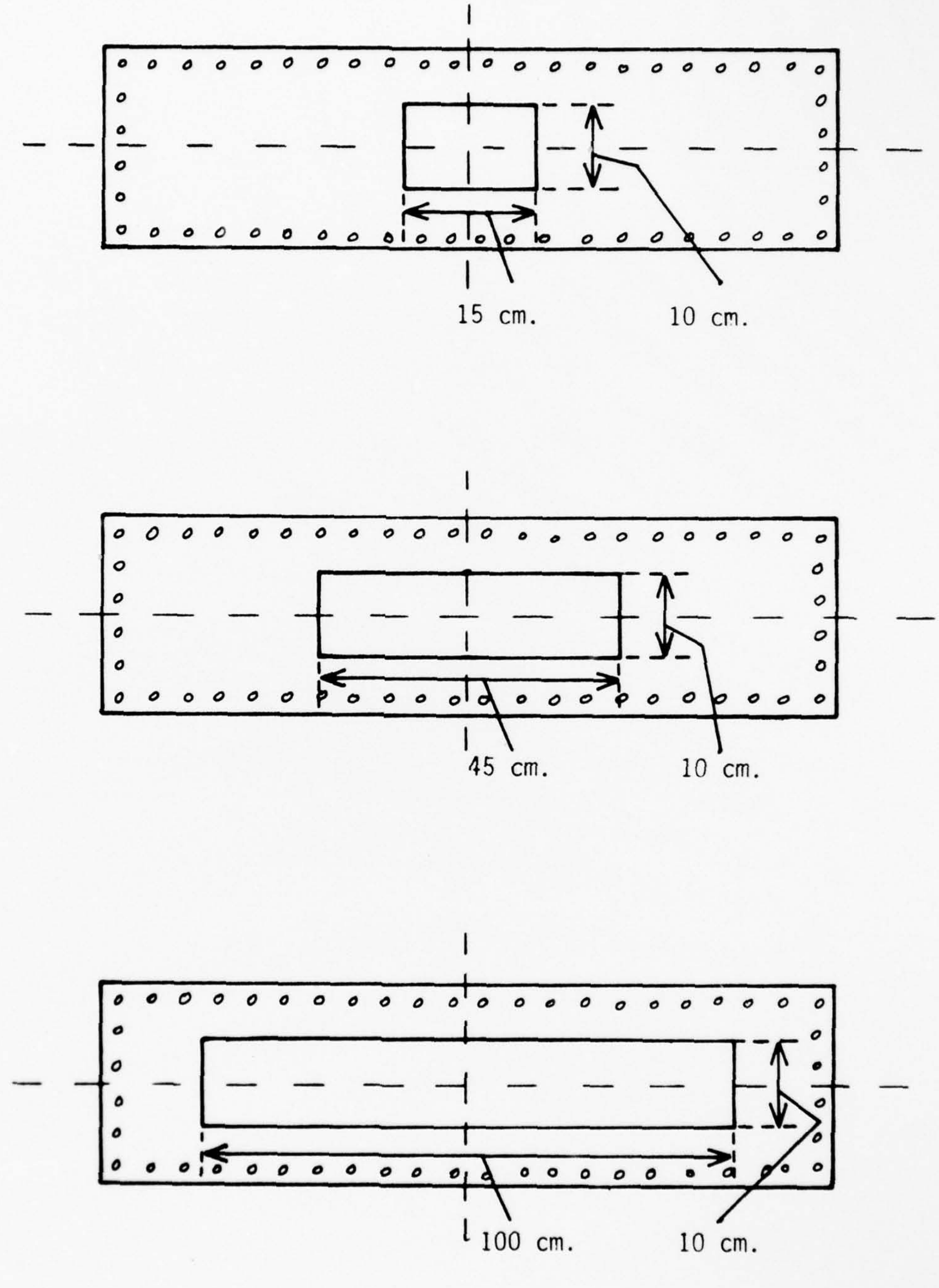


FIGURE 9 E-BEAM MASKS USED ON S^3 LASER FOR UAH TESTS.

f. Cavity Structures

The cavity structures serve to box-in the discharge region in the vertical and longitudinal directions and also to provide a support for the PVC pipe. Two structures were employed in this work; the 15 cm structure was used with the 15 cm mask while the 100 cm structure was used with both the 45 cm and 100 cm masks.

A sketch of a cavity structure is shown in Figure 10. Both the 15 and 100 cm structure were constructed in the same manner with only the dimension of the opening being different.

2. Muffler

In consultation with Mr. Cason of MICOM, a muffler was designed, constructed, and tested in the recirculation system. The location of the muffler in the system is shown on Figure 8. The muffler has no obstructions to the flow and was constructed to attach easily to the 4" PVC system. The physical dimensions of the muffler are shown in Figure 11.

3. Reflectors

The reflectors tested are shock wave attenuating and/or reflecting materials with frontal configurations of honeycomb and square. The honeycomb is made of aluminum and the square is made of THERMACOMB alumina ceramics. Table I presents the measured and calculated physical properties of the materials.

Table I

Type of Openings	Specimen Thickness(in)	No. of Openings per linear in.	Wall Thickness(in)	Percent Open Area	Hyd.Rad. per Open.(in)
Honeycomb	2.0	4.5	0.00075	92.86	0.0245
Square I	0.5	9	0.0044	85.14	0.0146
Square II	1.068	7.5	0.0090	74.29	0.0170

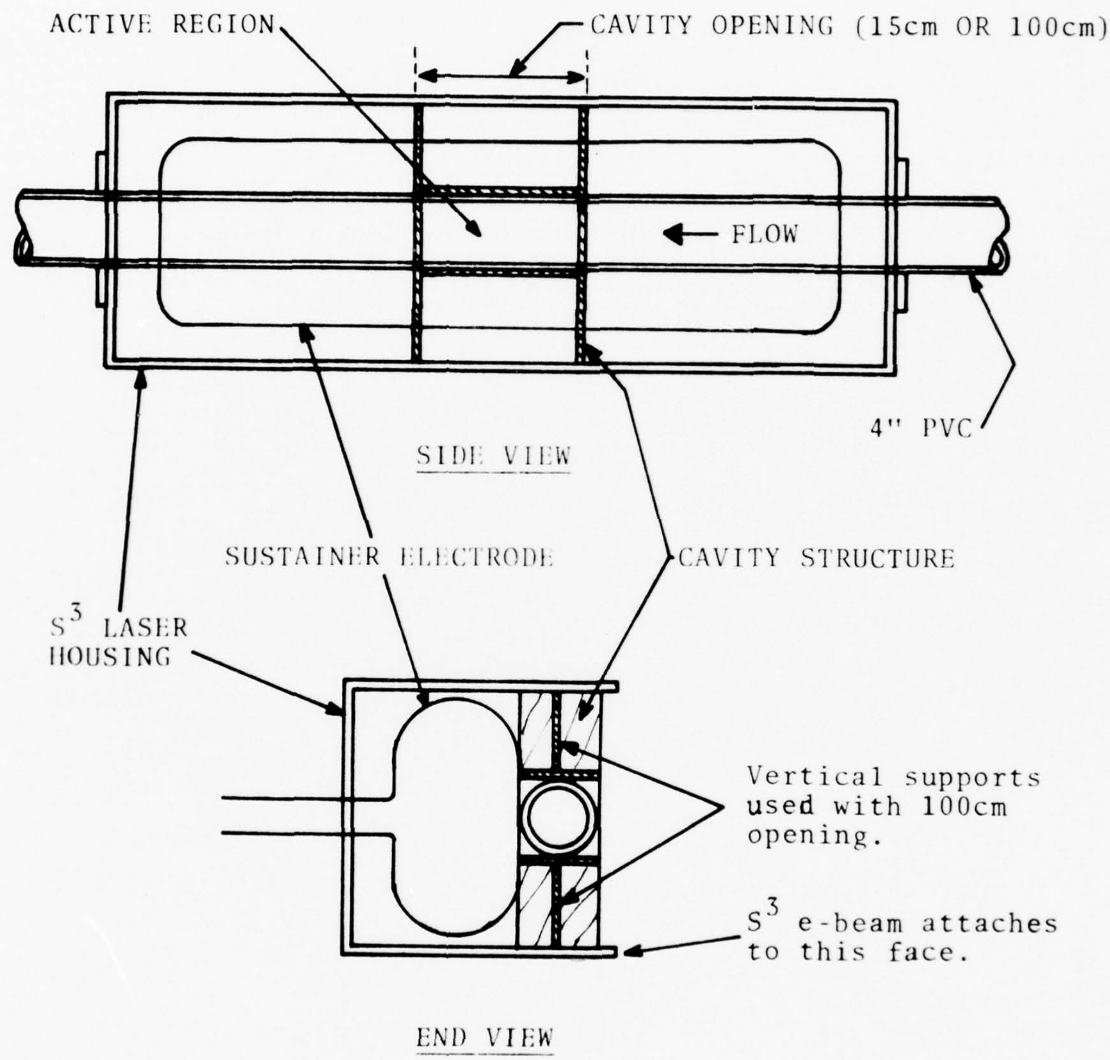


FIGURE 10. SKETCH OF CAVITY STRUCTURE AND INSTALLATION INSIDE THE S^3 LASER HOUSING.

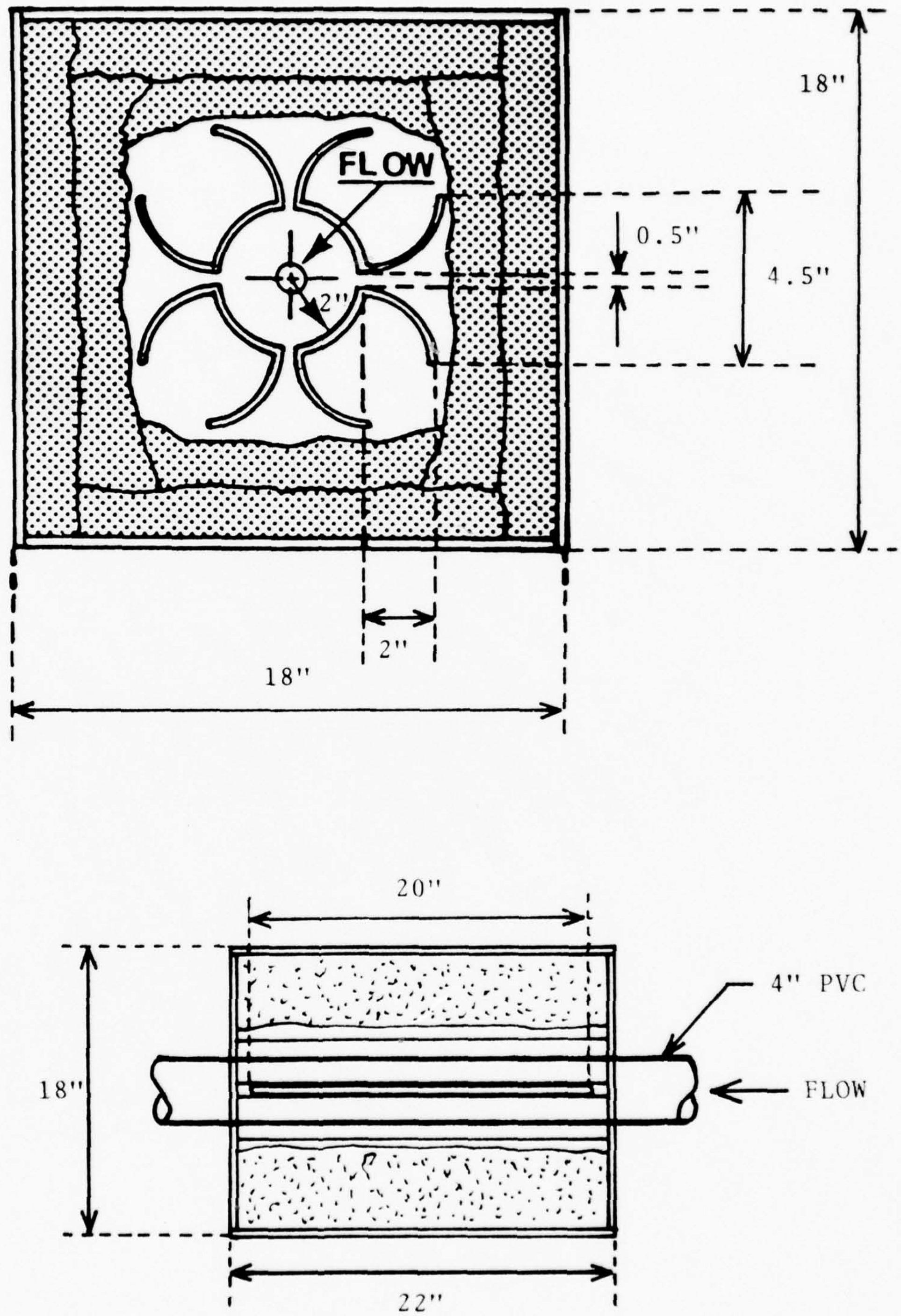
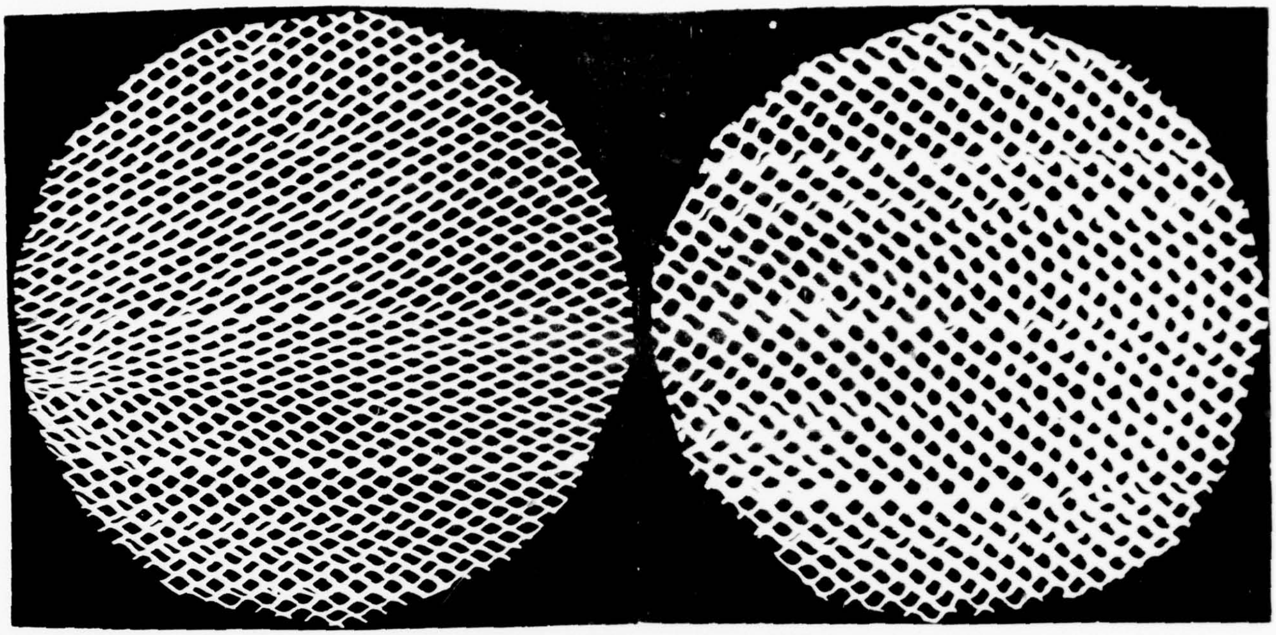
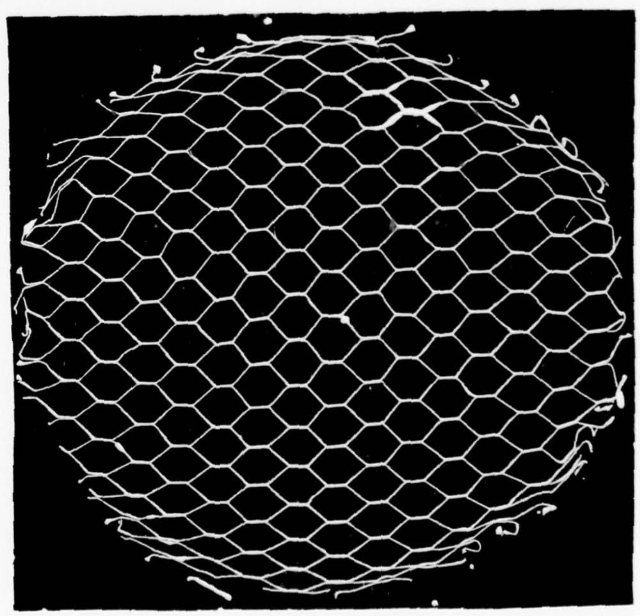


FIGURE 11. SKETCH OF MUFFLER.
Curved pieces constructed of 4" PVC piping, sides of box constructed of ¼" plywood, and end pieces constructed of ½" plexiglass.

Calculated values of the hydraulic radius $\left(\frac{\text{Area}}{\text{Wetted Perimeter}}\right)$ and percent open area are based on an average of the appropriate measured values. Frontal appearances of these gratis materials are shown in Figure 12. These reflectors are placed in the flow apparatus for a series of tests to determine the effectiveness of wave attenuation.



Square I Square II



Honeycomb

Figure 12. Frontal Appearances of Reflectors

4. Instrumentation System

a. Pressure Measurement

The instrument used for pressure measurements is a battery of four Piezotron pressure sensing units each of which consists of a piezoelectric pressure transducer (Type 201B5) and a coupler (549B) connected with a 128M cable. The unit is then connected to an oscilloscope for the readout of voltage signals. Specifications of the Piezotron miniature pressure sensor or transducer, the Piezotron coupler, and the Textronix oscilloscope are presented in Appendix D.

The pressure of up to 100 psi was sensed by the mini-gage which gives a direct, high level, voltage signal with less than 100 ohms output impedance and high frequency response of 50 K HZ and low frequency response of 0.005 HZ. The sensor then converts the pressure into electrical voltage with bias of up to 11 $\pm$ 2 volts. The power required by the transducer to operate is supplied by the coupler, and the signal from the transducer to the readout equipment is transmitted through the coupler over a single inexpensive cable. This eliminates all of the inherent piezoelectric high impedance problems of electrical leakage, cable noise and signal attenuation and allows the transducers to be used in contaminated environments and with long and moving cables at low noise and without use of charge amplifiers.

The calibration of the transducers was performed at the factory, and the values of the calibration were noted to be, on the average for all probes, 50 mv per psi for the pressure measurement up to 100 psi. The calibration curve relating the voltage output and the pressure is noted to be quite lenient.

b. Temperature Measurement

Due to the extremely transient nature of temperature variation in the recirculating flow as a result of the pulsed laser operation, a sensor of high frequency response in excess of 1 K HZ is considered necessary for the temperature measurement. Search of an adequate sensor resulted in the selection of a hot-wire sensor made of 0.00015 in diameter tungsten wire coated with platinum powdery film. The hot-wire sensor is connected to the Temperature and Switching Module (Thermo-Systems Model 1040) which is in turn connected to the power supply (Model 1031-10A).

The Module consists of a bridge circuit and amplifier in an open loop configuration so the hot-wire sensor which is ordinarily used as an anemometer probe can be switched to function as a resistance thermometer. Since there is a linear proportionality between the voltage output and the temperature, the calibration can be simply performed by adjusting the zero and gain set potentiometers to a desired temperature range using the calibrate pots of two temperatures.

c. Velocity Measurement

For the measurement of velocities, hot-wire probes the same as those used for the temperature measurement is applied. The probe is connected to the constant temperature anemometer module (Model 1010A). The amplified output signal from the anemometer is sent to the Linearizer (Model 1005B) so that the voltage signal is processed in such a way that it became linearly related to velocity of the gas flow.

The use of these modules ensures the frequency response above 500 K HZ with power output as high as 1.5 amps. The noise associated with the anemometer is noted to be less than 0.007% equivalent turbulent intensity. Frequency response to the Linearizer is found to be up to 400 K HZ and the accuracy of linearization can reach $\pm$ 0.2%.

With these special features of the instrument, it is able to measure both average velocity and turbulence in one-dimension.

Calibration of the probe is performed by using a Thermo-Systems Calibrator (Model 1125) in accordance with the furnished instructions. The readout system for both temperature and velocity is the Tektronix type oscilloscope (Type 564-3A74-3B3).

B. Presentation of Experimental Data

An experimental run typically involved firing the S^3 laser and recording pressure, temperature or velocity at various locations in the recirculation system. Besides the pressure, temperature and velocity data, the laser discharge current was also monitored in order to determine the power put into the gas. Each firing of the S^3 laser was logged with respect to the sequence number. The first UAH experiment began with sequence number 3043 on December 7, 1976 and the last experiment was with shot number 3238 on February 2, 1977. The log of all the UAH shots is given in the table.

The tests were designed to investigate the fluid-thermal disturbances produced by the sudden energy deposition in the cavity region. In the following sections, we describe the wave forms produced by the laser, the wave interactions with the system components, and the wave attenuations within the system. Each of these topics will be divided into the pressure wave results and the thermal-velocity wave results if appropriate.

1. Wave Forms Produced by the High Energy Laser

The S^3 laser was operated as normal except that no attempt was made to produce lasing action. The S^3 laser merely served to deposit energy into the gas at the cavity section, thereby simulating the energy pulse that takes place in such a laser. The E-beam was operated at 90 KV,

LOG OF UAH SHOTS

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3043	12/7/76	N_2	Off		Pressure wave propagation with no obstructions
3044	"	"	On	41	"
3045	"	"	"	26.45	"
3046	"	"	Off	10.11	"
3047	"	"	"	28.22	"
3048	"	"		28.27	"
3053	12/8/76	"	Off	-----	Pressure wave propagation with large pore metal honeycomb placed at heat exchanger locations
3054	"	"	On	-----	
3058	12/9/76	"	-	9.46	Pressure & temperature wave propagation tests with large pore metal honeycomb at heat exchanger locations
3059	"	"	On	15.51	
3060	"	"	"	18.45	"
3061	"	"	"	15.83	"
3062	"	"	"	13.88	"
3064	"	"	"	14.67	"
3065	"	"	"	10.13	"
3066	"	"	"	10.33	"
3067	"	"	"	14.63	"
3068	"	"	"	14.67	"
3069	"	"	-	11.50	"
3070	"	"	Off	11.00	"
3071	"	"	On	13.32	"
3075	12/10/76	Ar	Off	56.65	"
3076	"	"	On	56.65	"
3077	"	"	"	-----	"

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3079	"	"	"	8.20	Pressure wave tests with two 27 mm sections of cer honeycomb between stations 3 and 4
3080	"	"	Off	9.24	"
3082	"	"	"	7.04	"
3083	"	"	"	8.80	"
3084	"	He	"	8.67	"
3085	"	"	On	9.35	"
3086	"	"	"	12.97	"
3087	"	"	"	12.97	"
3088	"	"	Off	19.59	"
3089	"	"	"	12.07	"
3090	"	Ar	On	30.12	"
3092	"	"	"	26.60	"
3093	"	"	Off	22.63	"
3094	"	"	"	26.10	"
3095	"	"	On	27.9	"
3096	12/14/76	"	"	39.2	Pressure wave propagation tests with 4 sections of cer honeycomb between stations 3 and 4
3097	"	"	"	25.66	"
3098	"	"	Off	17.87	"
3099	"	"	"	13.32	"
3100	"	"	"	9.75	"
3101	12/17/76	"	On	19.76	Pressure wave propagation tests with muffler placed between stations 3 and 4
3102	"	"	"	21.88	"
3103	"	"	"	12.00	"

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3104	12/17/76	Ar	Off	9.93	"
3105	"	"	"	18.5	"
3106	"	"	"	27.28	"
3107	12/20/76	"	"	42.90	Pressure wave propagation through muffler to get good record of wave history
3108	"	"	"	51.73	
3109	"	"	"	49.07	"
3110	"	"	"	54.75	"
3111	"	"	"	49.07	"
3112	"	"	On	32.55	"
3113	"	"	"	26.35	"
3114	"	"	"	13.78	"
3115	"	"	"	37.40	"
3116	"	"	"	25.6	"
3117	"	"	"	-----	"
3119	12/21/76	"	Off	58.88	"
3120	"	"	"	62.06	"
3121	"	"	"	70.40	"
3122	"	"	"	55.15	"
3123	"	"	"	50.17	"
3124	"	"	"	61.60	"
3125	"	"		66.67	"
3127	"	"	On	58.67	"
3128	"	"	"	60.00	"
3129	"	"	"	53.40	"
3130	"	"	"	54.40	"

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3131	12/22/76	Ar	Off	91.87	Pressure wave tests with new probe location near muffler and time delayed signals
3132	"	"	"	83.33	"
3133	"	"	"	79.12	"
3134	"	"	"	98.58*	"
3135	"	"	On	66.75	"
3136	"	"	"	52.13	"
3137	"	"	"	40.13*	"
3138	"	N_2	"	53.67	"
3139	"	"	"	35.00*	"
3140	"	"	Off	48.42*	"
3141	"	He	On	55.73	"
3142	"	"	"	45.68*	"
3143	"	"	Off	52.70*	"

*Enlargements made of scope traces for purpose of data analysis

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3144	1/7/77	N_2	Off		All four pressure probes put at same location to test relative responses.
3145	"			50.0	
3146	"			49.9	
3147	"			53.	
3150	1/25/77	Argon		51.3	Installed new probe at up-stream of discharge to test effect of corner.
3151	"	"		32.0	
3152	"	"	On		Also, thermal wave tests.
3153	"	"	"	30.7	
3154	"	"	"	30.8	
3155	1/26/77	N_2	"	47.6	
3156	"	"	"		
3157	1/27/77	"	"	23.1	
3158	"			17.8	Corner and thermal wave test in N_2.
3159	"	N_2	Off	17.5	
3160	"	"	"		Thermal wave at different locations around system.
3161	"	"	On	29.0	
3162	"	"	"	34.8	
3163	"	"	"	22.7	
3164	"	"	"	26.9	
3165	"	"		34.0	Wave near muffler.
3166	"	"	On	26.5	
3167	"	"	"	25.3	
3168	"	He	"	52.8	Wave propagation and thermal wave.
3169	"	"	"	18.0	
3170	"	"	"	20.7	
3171	"	"	"	38.5	
3172	1/28/77	N_2	"	62.0	Muffler incident and reflection test and thermal wave.
3173	"			53.6	
3174	"	N_2	Off	39.6	
3175	"	"		31.2	
3176	"	"	Off	25.3	

ALL OF THE ABOVE TESTS USED A 15 CM CAVITY REGION

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
		THE FOLLOWING TESTS USE A 100 CM CAVITY REGION			
3177	2/1/77	N_2		>>126	Muffler incident reflection tests and thermal wave tests.
3178	"	"	On	208	
3179	"	"	"	312	
3180	"	"		182	
3181	"	"	On	186	
3182	"			300	Corner test and thermal wave.
3183	"	N_2		303	
3184	"	"		308	
3185	"	"	On	280	
3186	"	"	"	288	
3187	"	"	Off	303	Corner test with probes reversed.
3188	"	"	On	325	
3189	"	"	"	221	Muffler transmission test.
3190	"			165	
3191	"	N_2	On	187	
3192	"	"	"	194	
3193	"	"	"	184	
3194	"	"	"		
3195	"	"	"	294	
3196	"	"	"	128	
3198	"	"		290	Muffler reflection and incident test
3199	"				
3200	"	N_2	On		
3201	2/2/77	Argon	On	333	
3202	"	"	"	277	

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3203	2/2/77	Argon		280	
3204	"	"	On	232	
3205	"	"	"	242	
3206	"	"	"	294	Muffler transmission test
3207	"	"	"	239	
3208	"	"		305	
3209	"	"		260	Thermal wave tests
3210	"			400	
3211	"	Argon	On	390	Thermal wave and corner test
3212	"	"	"	347	
3213	"	"	"	372	Thermal wave and Fan Reflection Test
3214	"	"	"	260	
3215	"	"	"	371	
3216	"	"	"	307	
3217	"	"		322	Fan transmission test and thermal wave test
3218	"	"		300	
3219	"	"		289	
3220	"	"		350	

Reference Number	Date of Test	Gas Used	Blower Status	Energy of Pulse, J	Purpose of Test
3221	2/2/77	Argon		146	Fan transmission test and thermal test
3222	"	"		154	
3223	"	"		158	
3224	"	"		183	Fan reflection and incident test
3225	"	"		128	
3226	"	"	On	172	Corner test and thermal wave tests
3227	"	"	"	154	
3228	"	"	"	135	
3229	"	"	"	131	Muffler reflection and incident test
3230	"	"	"	197	
3231	"	"	"	179	
3232	"	"	"	171	
3233	"	"	"	203	Muffler transmission test
3234	"	"	"	168	
3236	"	"	"	205	
3237	"	"	"	104	Corner test
3238	"	"	"	122	

<u>THE ABOVE TESTS USE A 45 CM CAVITY REGION</u>

the sustainer voltage was varied between 15-30 KV, and the pulse width was varied between 2 and 3 μ sec. As pertains to the fluid dynamics of the cavity flow, the energy deposition is instantaneous and, therefore, the process can be described as an instantaneous constant volume heating process. The gas pressure and temperature are instantaneously increased by the energy deposition while the density remains unchanged. The following describes waves found produced by these initial conditions.

a. Pressure Wave Form

The pressure wave produced by the energy deposition consists of a sharp pressure rise followed by a sharp pressure drop and a negative phase. This is illustrated in Figure 13 where the pressure shown is positive in the negative direction since this is the way the data from the pressure transducers are recorded on the scope pictures. The width of the positive pressure pulse is typically 1 m sec and the negative phase has about the same width. The amplitude of the positive phase was a function of the energy deposited in the gas which varied between 7 and 100 J for the 15 cm cavity, between 120 and 400 J for the 100 cm cavity, and between 100 and 205 for the 45 cm cavity. (See log). The amplitude of the negative phase was generally proportional to the amplitude of the positive phase. Figures 14, 15, and 16 show a typical pressure wave for the 15, 45, and 100 cm cavity lengths respectively. Figure 14 for the 15 cm cavity shows the wave for the three different gases used in those tests (N_2, Ar, and He). Only Ar gas was used in the 45 cm tests and a typical wave form is shown in Figure 15. Both N_2 and Ar were used in the 100 cm tests and these results are shown in Figure 16. The 100 cm wave form shows two additional positive pressure pulses following the negative phase of the wave. This feature is not present in the 15 or 45 cm results.

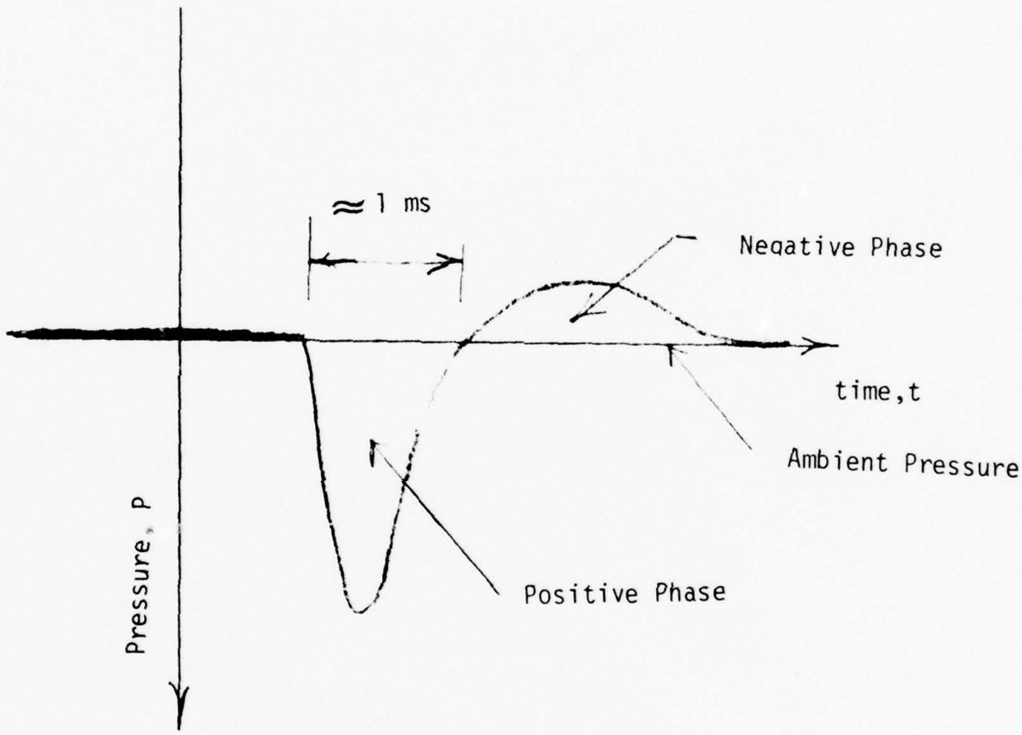


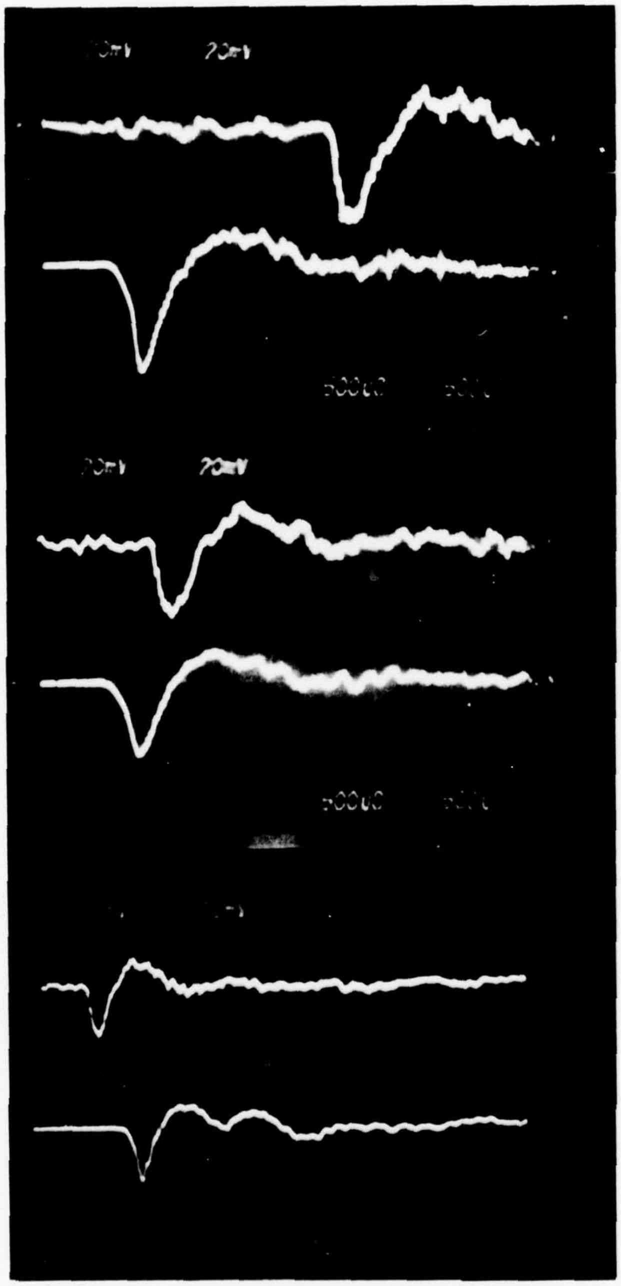
FIGURE 13. PRESSURE WAVE FORM CHARACTERISTICS.

All the results shown in Figures 14, 15, and 16 are for the case with the fan on. The character of the wave generated by the laser with the fan off is shown in Figure 17 for the 15 cm case and He gas.

b. Thermal Wave Form

The pressure waves described above travel away from the cavity, both upstream and downstream, at speeds greater than sonic. The pressure in the cavity region is adjusted back to a value near ambient in a short period of time. The temperature discontinuities created by the energy deposition do not, however. A hot region of gas remains long after the pressure waves have traveled away. The center of this hot region of gas moves away from the cavity at the speed of flow of the gas through the cavity. In measurements made very near the laser cavity, the hot region of gas was found to have the general shape as sketched in Figure 18.

Figure 19 shows the actual measured profiles for the 15 cm cavity for the N_2, Ar, and He gases. The probe was located at location # 1 which is 143.5 cm away from the center line of the discharge region. Figure 20 shows the profile for the 45 cm cavity using Ar gas. Figure 21 shows the measured temperature profiles for the 100 cm case for N_2 and Ar gas.



Shot # 3155
Date 1/26/77

Vertical Scale .02v/d
Horizontal Scale .5 msec/d

Notes
N_2
Fan On

Shot # 3154
Date 1/25/77

Vertical Scale .02v/d
Horizontal Scale .5 msec/d

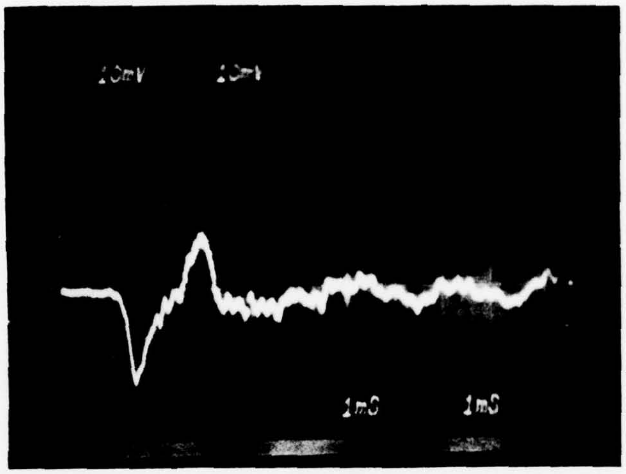
Notes
Argon
Fan On

Shot # 3170
Date 1/27/77

Vertical Scale .02v/d
Horizontal Scale 1 msec/d

Notes
He
Fan On

FIGURE 14. EXAMPLES FOR PRESSURE WAVE FORM FOR THE 15 CM CAVITY WITH N_2, Ar, AND He.

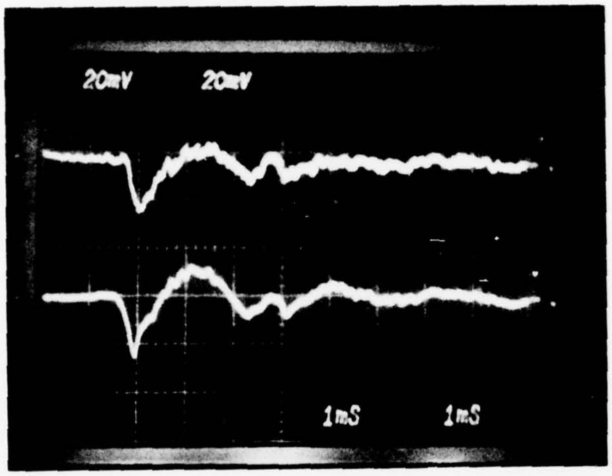


Shot # 3227
Date 2/2/77

Vertical Scale .01v/d
Horizontal Scale 1 msec/d

Notes
Argon (45 cm)
Fan On
Corner Test

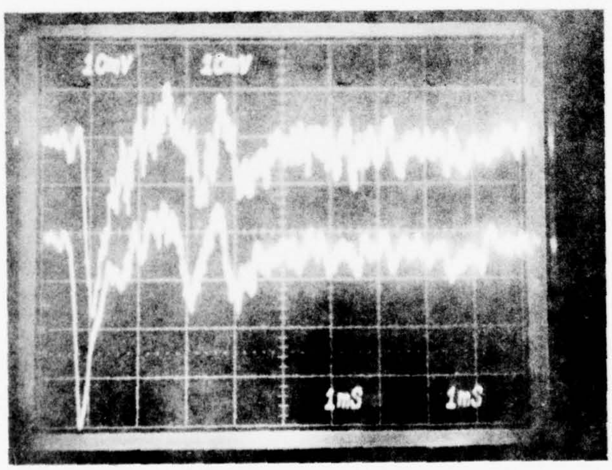
FIGURE 15. EXAMPLE OF PRESSURE WAVE FORM GENERATED BY 45 CM CAVITY USING Ar GAS.



Shot # 3181
Date 2/1/77

Vertical Scale .02v/d
Horizontal Scale 1 msec/d

Notes
N_2 (100 cm)
Fan On
A After Laser
B Before Muff

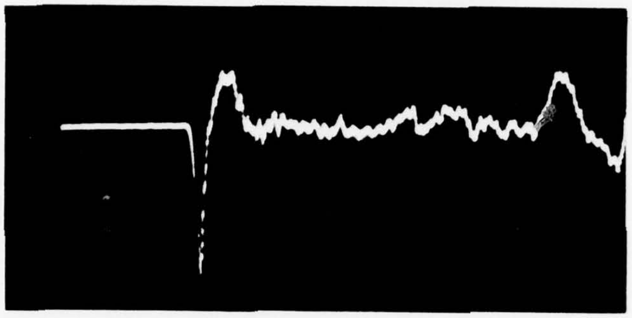


Shot # 3211
Date 2/2/77

Vertical Scale .01v/d
Horizontal Scale 1. msec/d

Notes
Argon (100 cm)
Fan On
Corner Test

FIGURE 16. EXAMPLES OF PRESSURE WAVE FORM GENERATED BY 100 CM CAVITY USING N_2 AND Ar GASES.



Shot # 3143

Vertical Scale .02v/d
Horizontal Scale 2 msec/d

Notes
Muffler

FIGURE 17. EXAMPLE OF PRESSURE WAVE WHEN FAN IS OFF. THIS IS FOR 15 CM CAVITY AND He GAS.

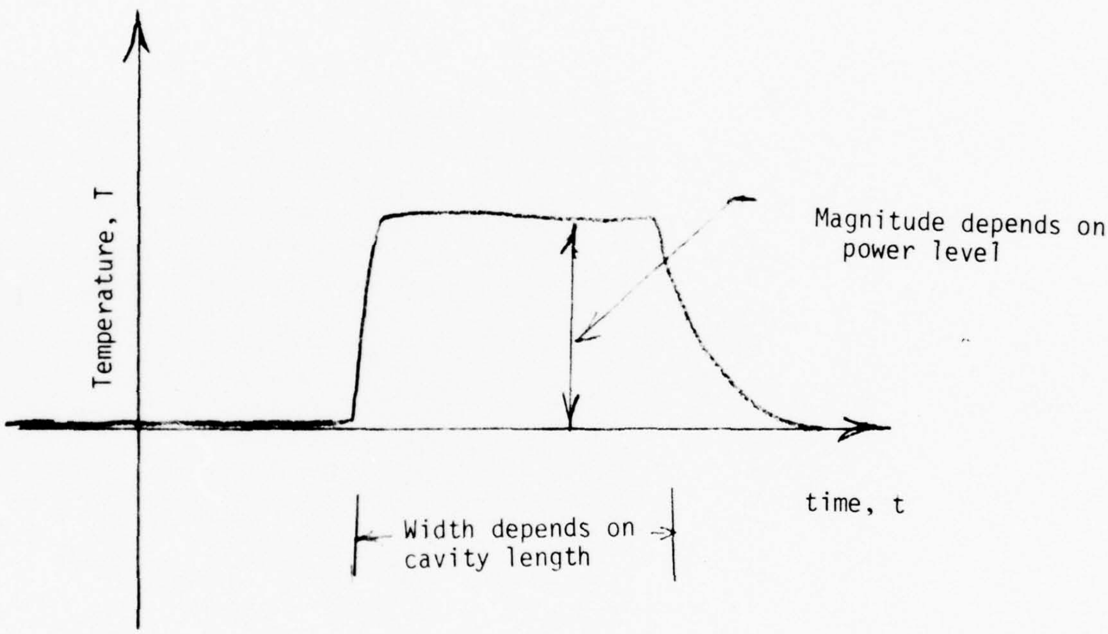
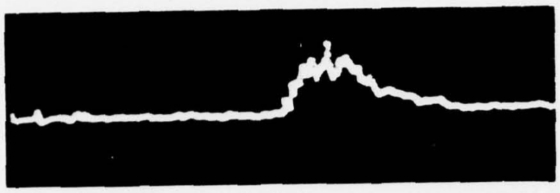


FIGURE 18. THERMAL WAVE FORM CHARACTERISTICS.



Shot # 3154
Date 1/25/77

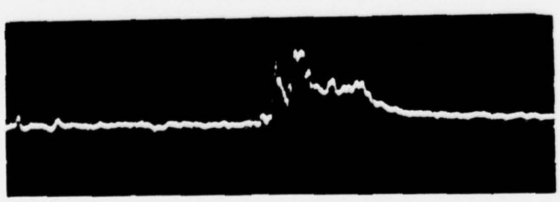
Vertical Scale on picture
Horizontal Scale 10 msec/d

Notes
Argon
Fan On

Shot # 3155
Date 1/26/77
Vertical Scale
Horizontal Scale 10 msec/d

Notes
N_2

Fan On

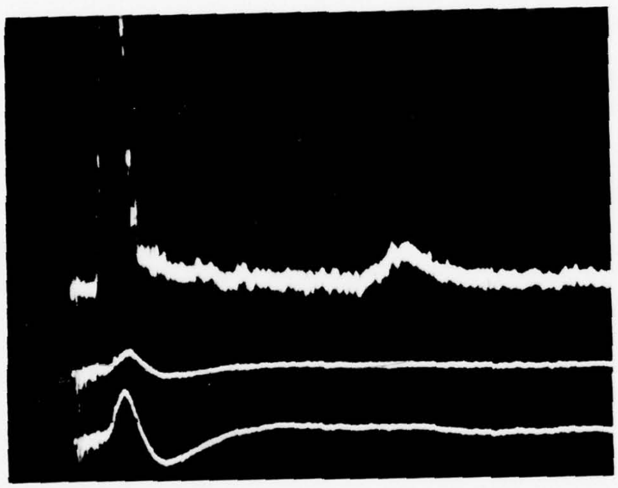


Shot # 3170
Date 1/27/77

Vertical Scale
Horizontal Scale 10 msec/d

Notes
He
Med. power

FIGURE 19. EXAMPLES OF THERMAL WAVE FORM FOR THE 15 CM CAVITY WITH Ar, N_2, AND He GAS.

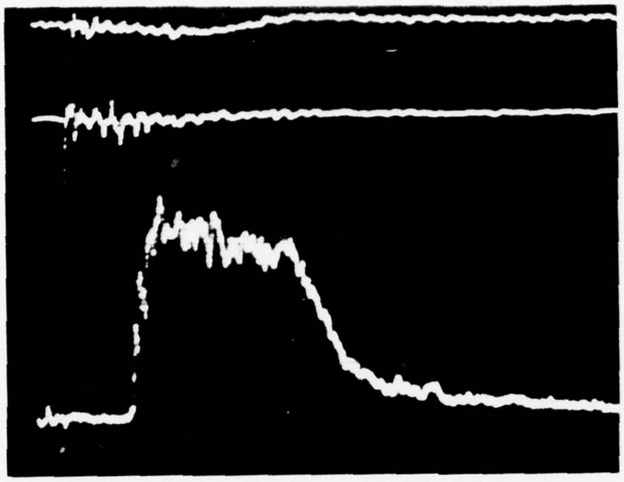


Shot # 3226
Date 2/2/77

Vertical Scale below
Horizontal Scale .1 sec/d

<u>Notes</u>
Argon
T @ 1 .1v/d
P_a @ 1 .02v/d
P_c @ 1 .02v/d

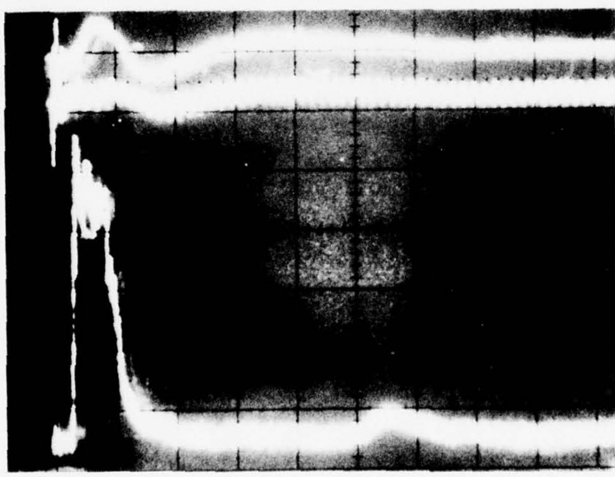
FIGURE 20. EXAMPLE OF THERMAL WAVE (UPPER TRACE) GENERATED BY 45 CM CAVITY USING Ar GAS.



Shot # 3180
Date 2/1/77

Vertical Scale
Horizontal Scale 20 msec/d

Notes
N_2 Medium Power
T .2v/d
P_c @ A Mu .02v/d
P_2 @ bend .02 v/d



Shot # 3217
Date 2/2/77

Vertical Scale below
Horizontal Scale .1 sec/d

Notes
Argon Medium Power
T @ 1 .2v/d
P_A @ 1 a (upstream of blower) .02v/d
P_C @ 1 .02v/d

FIGURE 21. EXAMPLES OF THERMAL WAVE (LOWER TRACE IN BOTH EXAMPLES) GENERATED BY 100 CM CAVITY IN N_2 AND Ar GAS.

2. Wave Interaction with Blower

The blower is the first system component the waves encounter upon leaving the downstream side of the cavity. The experimental results show that much of the pressure wave is reflected back toward the cavity. The thermal wave passes through the fan without reflection but is reduced in amplitude and spread over a larger distance.

The general characteristic of the pressure wave interaction with the fan is illustrated in Figure 22. All these features can be seen on a typical trace shown in Figure 23 where the upper trace is from a probe on the upstream side of the fan and the second trace is from a probe on the downstream side.

The thermal wave interaction with the blower is illustrated by the data shown in Figure 24 for shot numbers 3217 and 3219. For shot number 3217, the temperature probe is on the upstream side of the blower while for shot number 3219 the probe is on the downstream side of the blower. The power levels for the two shots are 322J and 289J respectively.

3. Wave Attenuation with Respect to Distance

Figure 24 illustrates the effect of distance of propagation on the thermal wave in the record for shot number 3217. The time sweep was set at .1 s/div so that the second passage of the wave could be observed at this same location. The experiment shows that the thermal wave took about .5 sec to travel around the system and was reduced in magnitude by a factor of about 8 after a single pass.

The attenuation of the pressure wave as it travels around the open system is shown in Figure 25 for shot number 3079 which shows the pressure probe records at the four major locations in the system. The effect of distance is seen by following the wave that travels upstream from the

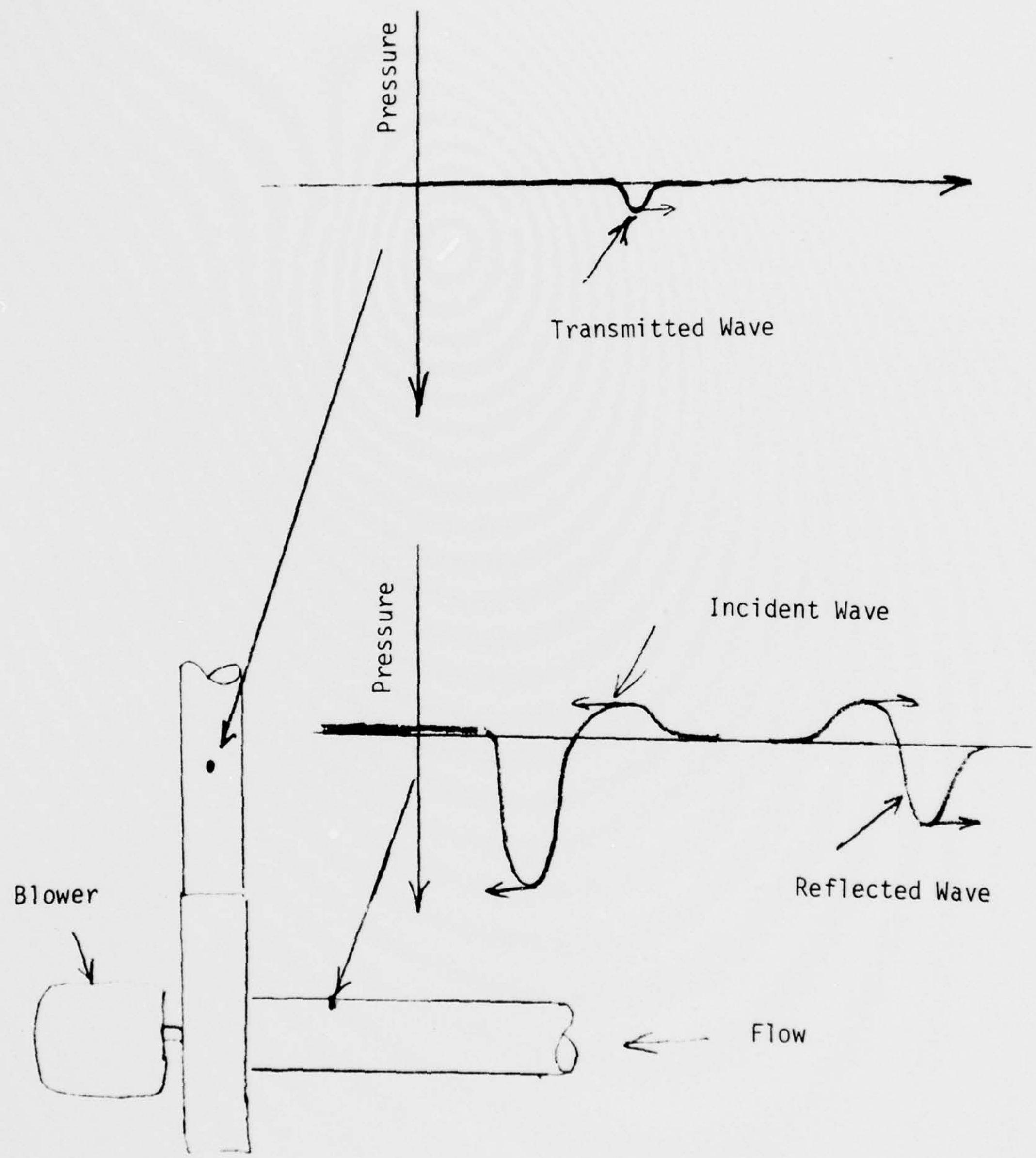
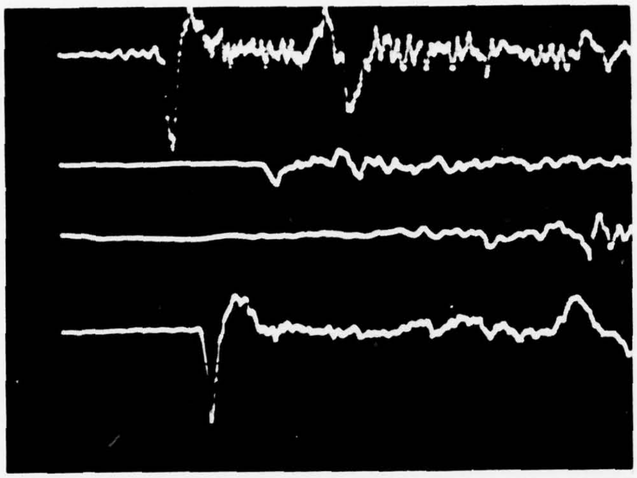


FIGURE 22. CHARACTERISTICS OF THE PRESSURE WAVE INTERACTION WITH THE BLOWER.

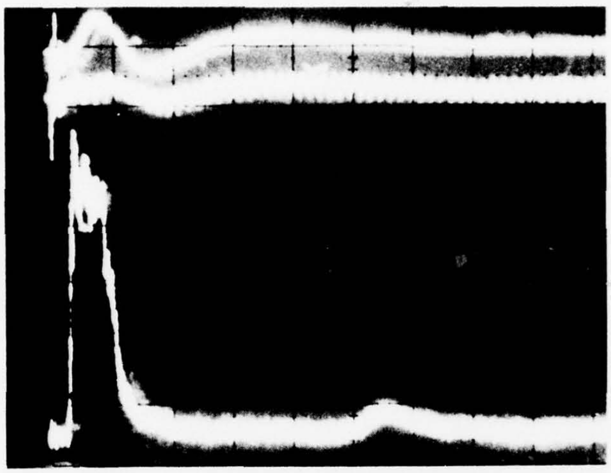


Shot # 3117
Date 12/20/76

Vertical Scale .02v/d
Horizontal Scale 2 msec/d

<u>Notes</u>
Argon
Muffler
Fan On

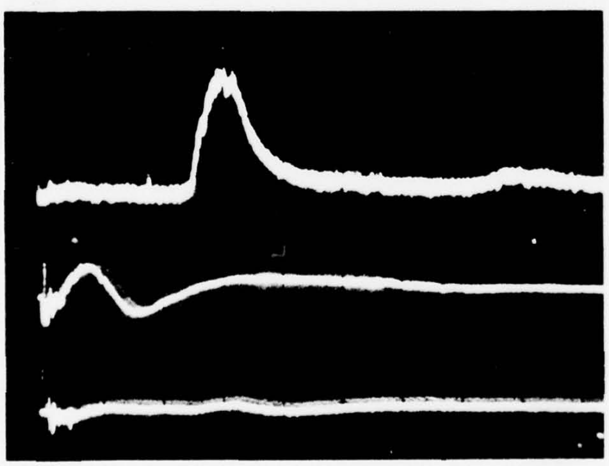
FIGURE 23. EXAMPLE OF PRESSURE WAVE INTERACTION WITH FAN (15 CM CAVITY ARGON GAS).



Shot # 3217
Date 2/2/77

Vertical Scale below
Horizontal Scale .1 sec/d

Notes
Argon
Medium Power
T @ 1 .2v/d
P_A @ 1 a(upstream of blower) .02 v/d
P_C @ 1 .02 v/d

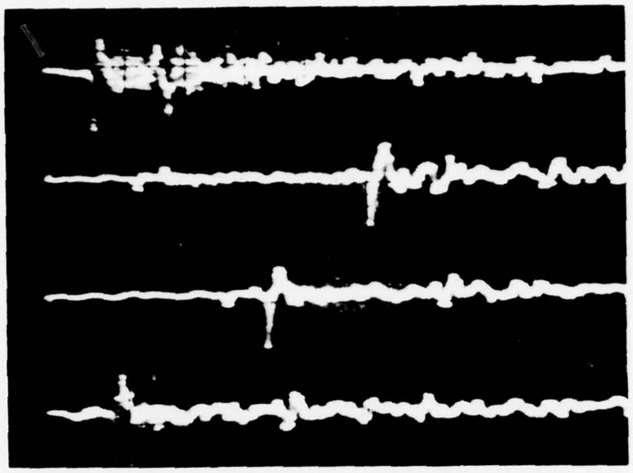


Shot # 3219
Date 2/2/77

Vertical Scale below
Horizontal Scale .1 sec/d

Notes
Argon
Medium Power
T @ uM .1v/d
P_A @ uM .02v/d
P_C @ 1 .02v/d

FIGURE 24. EXAMPLES OF INTERACTION OF THERMAL WAVE WITH THE FAN. LOWER TRACE OF #3217 IS TEMPERATURE PROBE UPSTREAM OF FAN WHILE UPPER TRACE OF 3219 IS TEMPERATURE PROBE DOWNSTREAM OF FAN.



Shot # 3079
Date

Vertical Scale .02 v/d
Horizontal Scale 5 msec/d

Notes

Argon	2 x 27 mm
Fan On	Cer honeycomb
90	Next to #4
15	

FIGURE 25. EXAMPLE OF PRESSURE WAVE PROPAGATION IN OPEN SYSTEM WITH THE FAN ON.

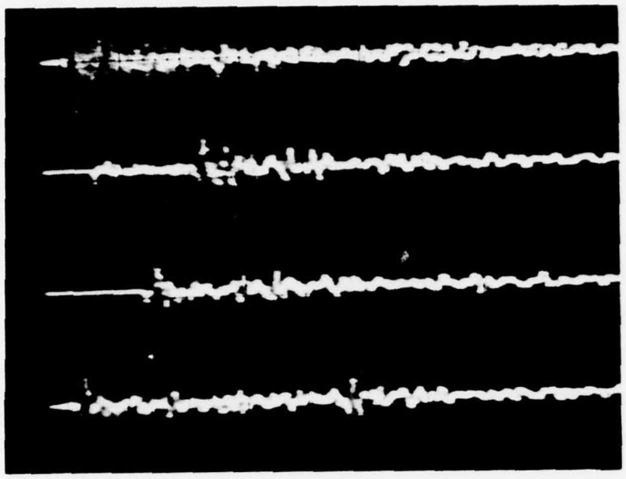
cavity beginning at station 4 then appearing at station 3 and finally at station 2. Taking the amplitude at station 4 as a reference, the positive phase amplitude at 3 and 2 is .718 and .684 respectively. These results are with the fan on. For the case when the fan is off, refer to Figure 26 which shows the results for shot number 3083. In this case, the amplitude at 3 and 2 relative to 4 is .814 and .804 respectively. This comparison shows that the pressure wave attenuation is much greater when the wave is traveling against the flow as compared to when there is no flow.

4. Pressure Wave Interaction with Ceramic Reflectors

The ceramic reflectors were installed between stations 3 and 4 in the recirculation system. The thin walled metal honeycomb was found to have no measurable effect on the wave propagation. The pressure wave was found to be attenuated by the square celled ceramic. They were not found to cause any measurable reflection of the pressure wave, however. Examples of the results are shown in Figure 27 for shot number 3097 with the fan on and number 3098 with the fan off. For these shots, all four sections (8 cm in total length) of the square celled ceramic were placed between stations 3 and 4. Using the amplitude at station 4 as the reference, the amplitude ratio across the ceramic was .562 with the fan on and .632 with the fan off. Compared with the same ratios discussed in part 3 above, the ceramic is found to reduce the amplitude of the pressure wave by a factor of .78 compared to the open pipe.

5. Pressure Wave Interaction with Muffler

The muffler was found to have a dramatic effect on the pressure wave as can be seen in Figure 28 which shows the results for shot numbers 3102 and 3106 for fan and no fan respectively. The pressure wave



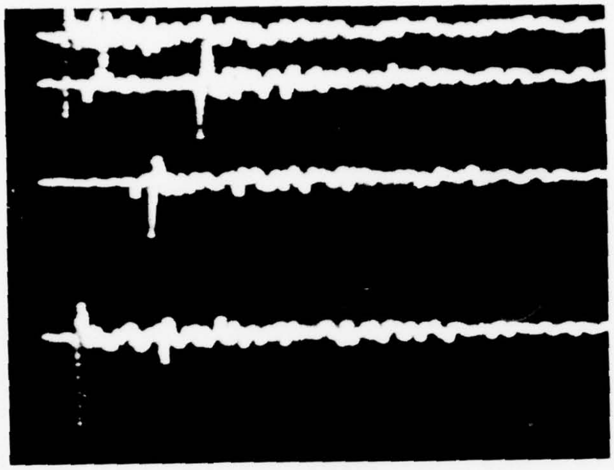
Shot # 3083

Date

Vertical Scale .02v/d
Horizontal Scale 10 msec/d

Notes
90
115.8
No Fan
Argon

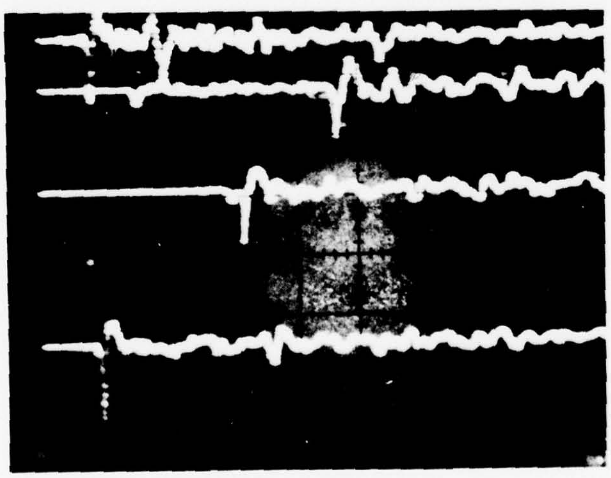
FIGURE 26. EXAMPLE OF PRESSURE WAVE PROPAGATION IN OPEN SYSTEM WITH THE FAN OFF.



Shot # 3097
Date 12/14/76

Vertical Scale .02v/d
Horizontal Scale 10 msec/d

Notes
Argon
4 sections of cer, fine
& coarse

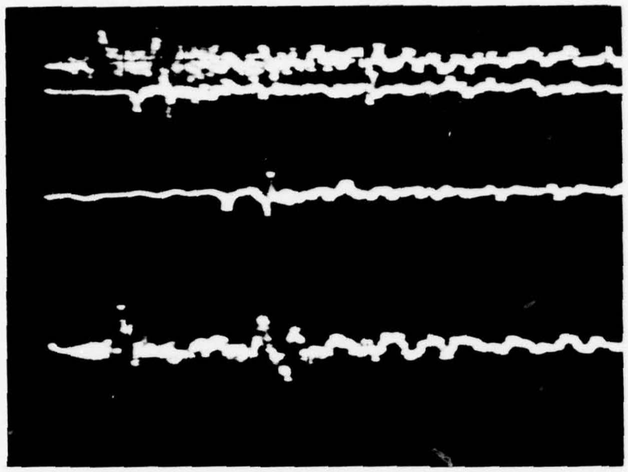


Shot # 3098
Date 12/14/76

Vertical Scale .02v/d
Horizontal Scale 5 msec/d

Notes
Argon
Fan Off
4 sections of Cer Honeycomb,
Coarse & Fine

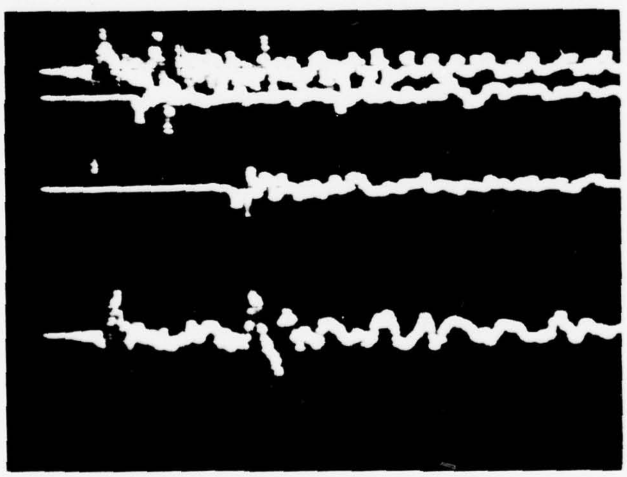
FIGURE 27. EXAMPLES OF PRESSURE WAVE PROPAGATION THROUGH CERAMIC REFLECTORS WITH FAN ON (#3097) AND FAN OFF (#3098).



Shot # 3102
Date 12/17/76

Vertical Scale .02 v/d
Horizontal Scale 5 msec/d

Notes
Argon
Muffler
Fan
90
21.8
Strong



Shot # 3106
Date 12/17/76

Vertical Scale .02v/d
Horizontal Scale 5msec/d

Notes
Argon
Muffler
28.9/90
No Fan
Long Pulse

FIGURE 28. EXAMPLES OF PRESSURE WAVE PROPAGATION THROUGH THE MUFFLER WITH THE FAN ON (#3102) AND FAN OFF (#3106).

amplitude ratio across the muffler is found to be .143 with the fan on (#3102) and .181 with the fan off (#3106).

Pressure probes were relocated nearer the muffler and a more detailed study was made of the pressure wave interaction with the muffler. This study showed that there is a negative phase pressure wave reflected from the muffler when the pressure wave travels into the muffler. The positive phase of the pressure wave is attenuated considerably in the muffler while the negative phase is not reduced as much. A sketch of the pressure wave interaction is given in Figure 29. Figure 30 shows data which supports the general view of the muffler interaction as shown in Figure 29. In Figure 30, data from shot numbers 3172 and 3143 are shown. For #3172, the two pressure probes are placed at the same side of the muffler spaced about 22 cm apart. In the lower trace of #3172, the reflected negative wave is on top of the negative phase of the incident wave. In the top trace, the reflected negative wave is seen separated from the incident pressure wave. The data on shot #3143 was taken with one pressure probe on each side of the muffler. The upper trace shows the transmitted wave and the lower trace shows the incident wave. The second negative phase wave on the lower trace of #3143 is the reflected negative phase wave as has been discussed.

The performance of the muffler was investigated in more detail with the assistance of Mr. Cason and Dr. Werkheiser of MICOM. They provided a pressure spectrum of the pulse which is typical of that generated in a laser pulse shown in Figure 30a. This figure shows that much of the energy in the pressure pulse is contained in the 100 to 1000 Hz range. The pressure wave data taken in laser firings Number 3134, 3137, 3139, 3140, 3142 and 3143 was photographically enlarged and over 100 data points taken from

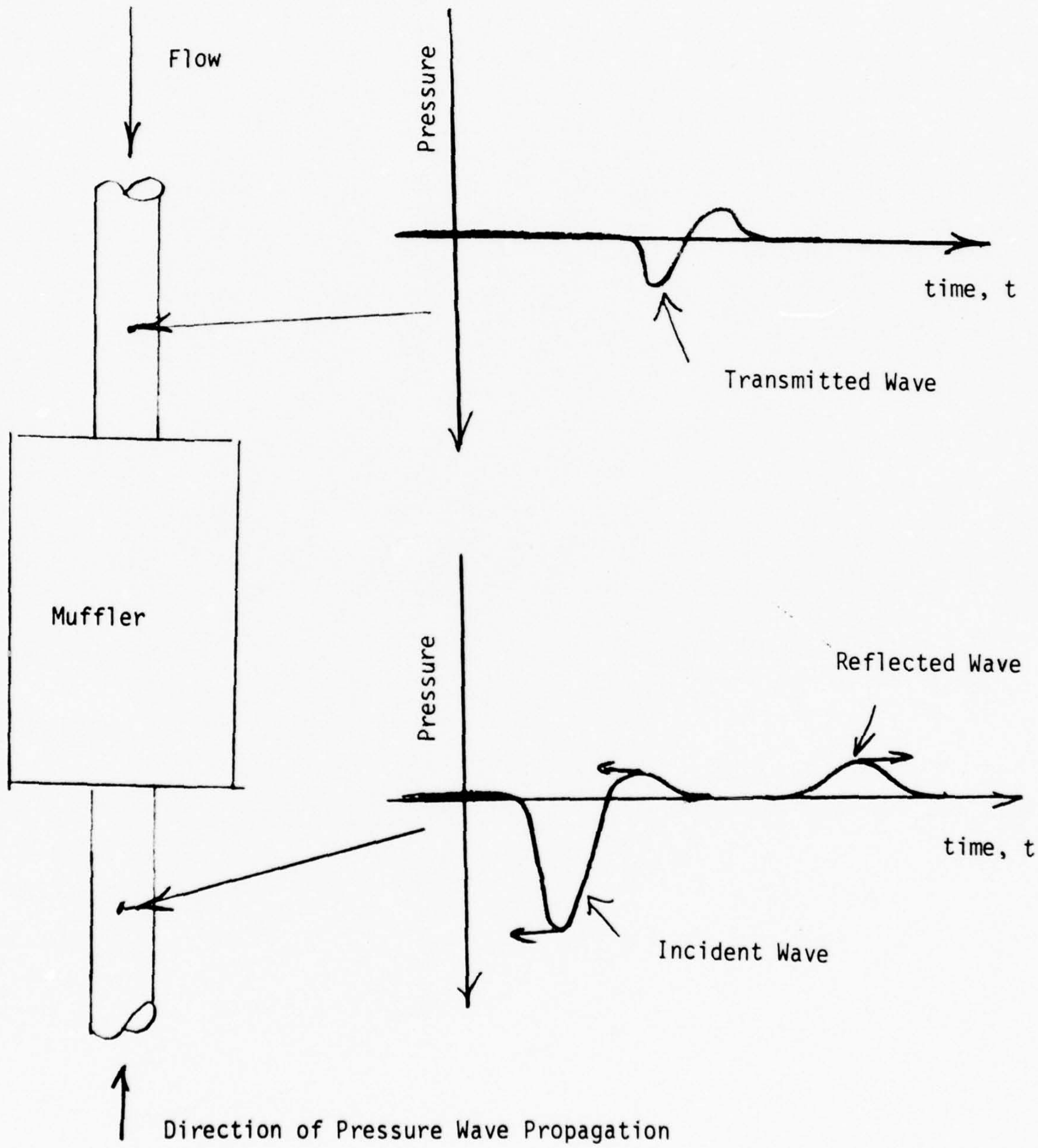
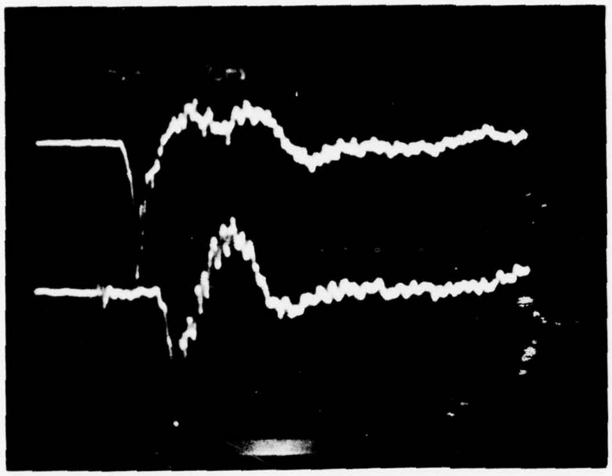


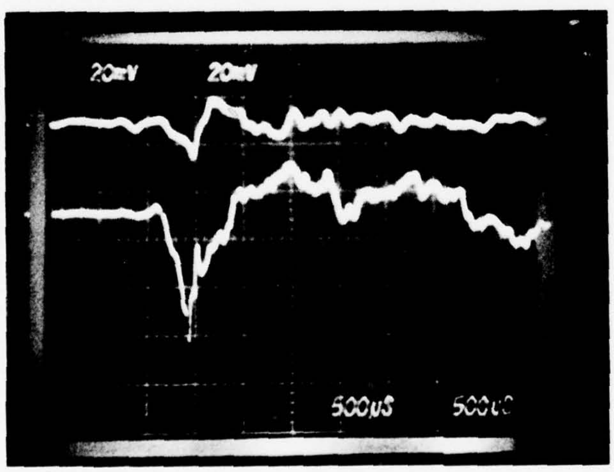
FIGURE 29. CHARACTERISTICS OF PRESSURE WAVE INTERACTION WITH MUFFLER.



Shot # 3172
Date 1/28/77

Vertical Scale .02 v/d
Horizontal Scale 1 msec/d

Notes
Both delayed 8 msec
N_2, Fan On
Muff Test



Shot # 3143
Date 12/22/76

Vertical Scale .02 v/d
Horizontal Scale .5 msec/d

Notes
He
Fan Off

FIGURE 30. EXAMPLE OF PRESSURE WAVE INTERACTION WITH MUFFLER; #3172 SHOWS THE INCIDENT AND REFLECTED WAVE, #3143 SHOWS THE TRANSMITTED WAVE.

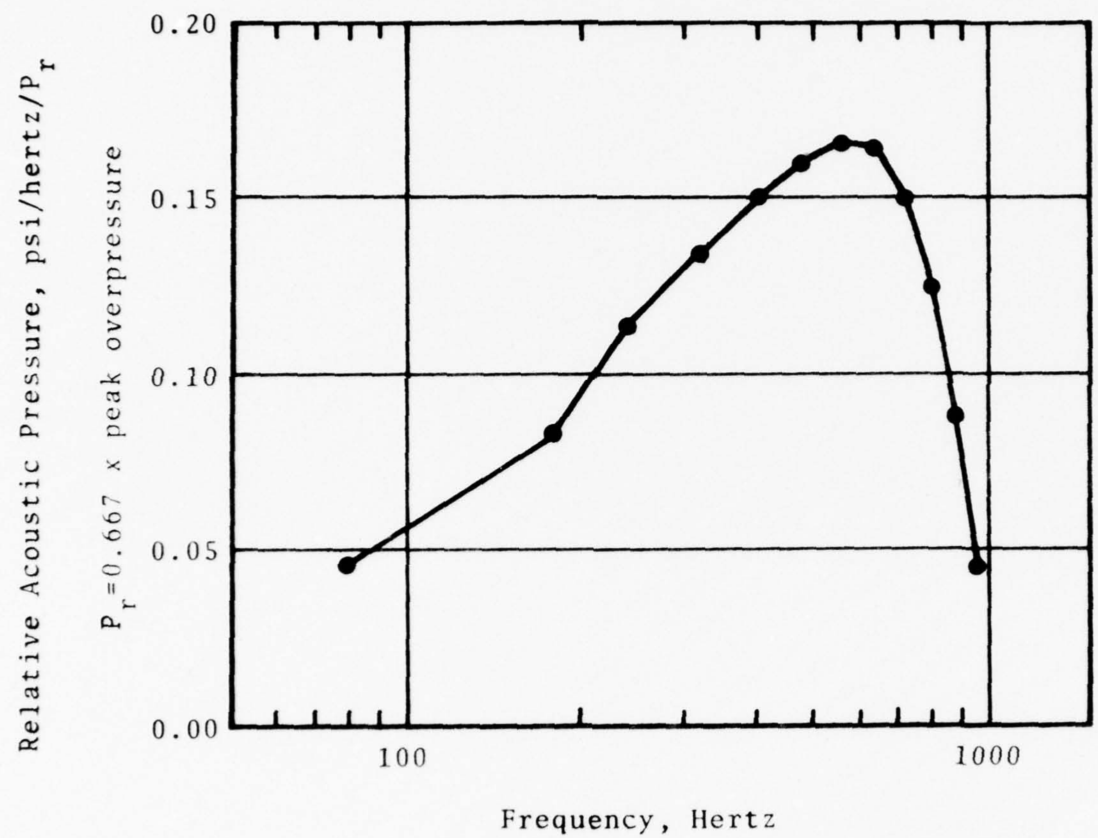


FIGURE 30a. ACOUSTIC PRESSURE SPECTRUM RESULTING FROM LASER FIRINGS.

each trace. These data were input into a computer program to obtain the power spectrum density of the incident and transmitted waves. From this data, the attenuation characteristics of the muffler was determined as a function of frequency. The results are shown in Figure 30b for three different gas mixtures.

The results show that nearly 40 db attenuation was obtained at the low frequency end and a 12 db peak at near 500 Hz. The first peak is likely due to the large volume available for resonance and the 500 Hz peak is likely resulting from the horn characteristics. The results show a need to design for the 100 to 200 Hz frequency range since this muffler had little effect on energy in that range. The range above 1000 Hz can likely be increased by lining the duct or other standard approaches for high frequency energy.

6. Pressure Wave Interaction with 90° Turns

Data was taken on the pressure wave at a location before and after it passed a 90° turn. No measurable change in the wave form could be observed and no measurable reflection could be observed. Samples of the data are presented in Figure 31 which shows data for shot numbers 3211 and 3238 for the 100 and 45 cm cavity cases with the fan on. The upper traces show the wave form before the corner and the lower traces show the wave form after the corner.

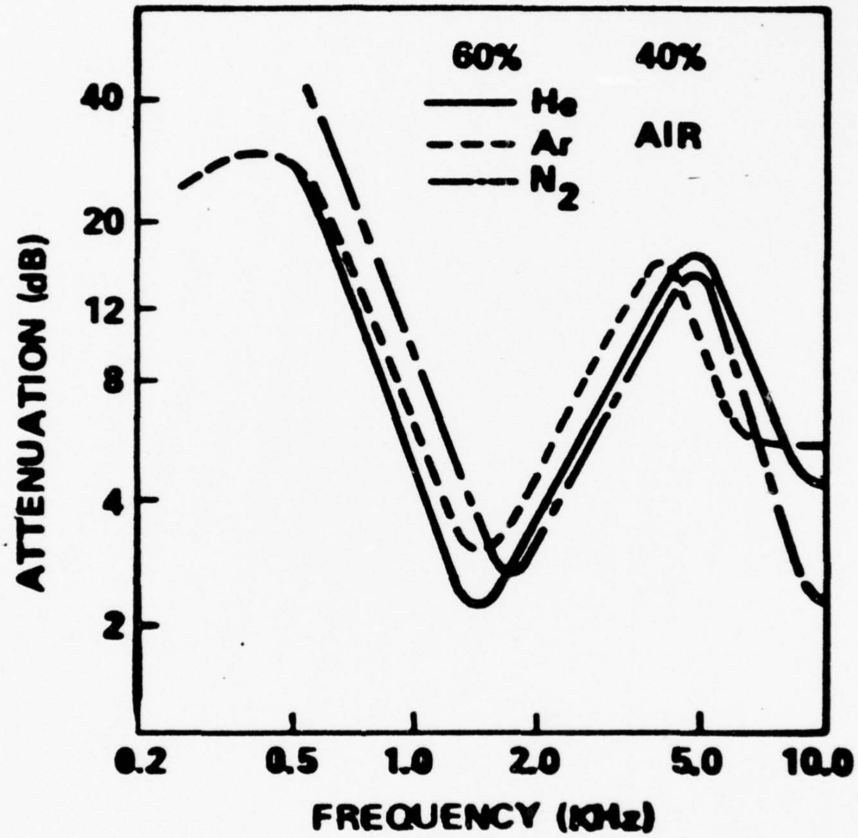
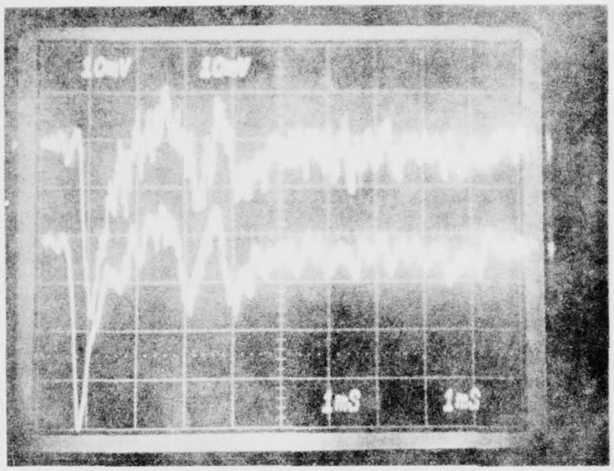


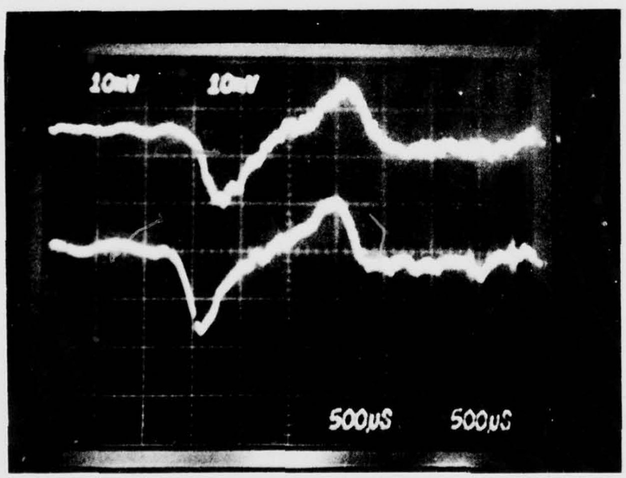
FIGURE 30b. ATTENUATION AS A FUNCTION OF FREQUENCY FOR THE HORN-COUPLED-RESONATOR MUFFLER WITH THREE DIFFERENT GAS MIXTURES.



Shot # 3211
Date 2/2/77

Vertical Scale .01 v/d
Horizontal Scale 1. msec/d

Notes
Argon
Fan On (100 cm)
Corner Test



Shot # 3238
Date 2/2/77

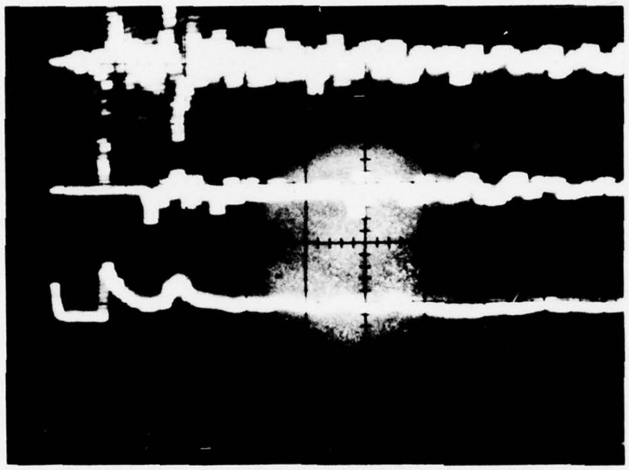
Vertical Scale .01 v/d
Horizontal Scale .5 msec/d

Notes
Argon (45 cm)
Fan On
Corner Test

FIGURE 31. EXAMPLES OF PRESSURE WAVE INTERACTION WITH CORNER. TOP TRACES SHOW WAVE BEFORE CORNER AND LOWER TRACE SHOWS SAME WAVE AFTER CORNER.

7. Velocity Wave Form

A limited amount of data was obtained from the hot wire on velocity waves in the system. An example of the results obtained on the velocity wave is shown in Figure 32 for shot number 3125. The third trace shows the velocity as measured at station 1. The upper trace is the pressure record at that same location. The results show the sudden change in velocity caused by the shock, the decay in velocity caused by the expansion wave following the shock, the sudden velocity increase caused by the shock traveling back past station 1 after reflecting off the fan, and the decay in velocity due to the traveling expansion fan.



Shot # 3125
Date

Vertical Scale below
Horizontal Scale 5 msec/d

Notes
90-26 power

Vertical Scale
p. 1 & 2 .2 v/d
vel 4 .5 v/d

FIGURE 32. EXAMPLE OF RESULTS OBTAINED ON VELOCITY WAVE TAKEN AT STATION # 1 NEAR THE EXIT TO THE LASER.

Chapter IV

DESIGN OF LASER CAVITY

The UAH team assisted Mr. H. C. Tom in the engineering design of the laser cavity to be incorporated in the laser system under design and construction. Periodical meetings were held to provide technical information and design guidance in the detail flow calculations, thermo analysis, and configuration design of the laser cavity. Some laboratory analyses using a water table was employed during this period in obtaining pertinent technical data for the design.

Chapter V

CONCLUSIONS

The theoretical and experimental program which was begun during the duration of this contract is not complete at this time but the following conclusions have been drawn based on the subscale testing and the numerical modeling work.

1. Impulsive high energy deposition in a flowing gas, characteristic of a high energy laser pulse, produces shock waves which travel at supersonic speeds, both upstream and downstream, away from the cavity. The energy pulse also produces a region of hot gas which travels with the flowing gas.

2. The shock waves travel throughout the recirculation system, travel around 90^{o} turns with little or no attenuation, reflect off a compressor with little or no attenuation, and can likely be absorbed by mufflers of suitable design.

3. The hot gas region (or thermal wave)moves at the flow velocity, is attenuated by the compressor, and will return to the cavity in one recirculation cycle unless suitable heat transfer takes place in the circuit.

4. One dimensional modeling of the transient flow behavior is able to predict the major qualitative characteristics of pulsed operation (i.e., the shock wave and thermal wave generation) but quantitative comparisons show a need for improved gas dynamic modeling of the transient behavior.

5. Acoustic absorbers of the honeycomb type tested in this work were found to be of little influence in the attenuation or reflection of the shock wave or the thermal wave. Either a much more closed honeycomb

or many more of the ones employed would be required to attenuate the shock wave. This would be at the expense of significantly higher pressure drop.

6. A low-pressure-drop muffler can likely be designed to eliminate the shock waves produced by the pulsed laser operation. The muffler tested in this work was successful in attenuating the shock wave by 40 db and better performance can likely be obtained by redesign and further testing.

7. The numerical simulation of steady state operation and transient fluid and thermal behavior needs further development which could come about from imperial relations based on actual system performance. The subscale system employed in the work reported here was not appropriate for development of the data needed on start up transients and heat exchanger performance.

The work reported here has revealed the major transient fluid and thermal characteristic of high energy gas laser systems operated in a pulsed mode. While the closed cycle EDL has been the basis for the study, the results should be of interest and application to the design of both closed and open cycle systems including electric discharge, chemical, and gas dynamic high energy systems. The closed cycly system presents the most severe environment in terms of pulsed operation since waves can travel around the system or reflect back to the cavity and thus spoil beam quality or otherwise degrade the gas properties desired for efficient laser operation. Wave attenuation is required in order to prevent waves from returning to the cavity region or from traveling into the upstream regions of the system. Such attenuation can most likely be performed using high pressure drop screens, honeycomb material, or orifice plates. The overall

efficiency of the laser system is, however, reduced by the use of high pressure drop devices and a better solution would be to employ low pressure drop muffler concepts. The muffler concept employed in the work reported here was of the straight flow type having no structure to impede the flow of laser gas. The waves are attenuated by designing resonate cavities and horn amplifiers to transmit the A. C. energy in the flow to be disipated in acoustic absorbing material while not effecting the D. C. energy contained in the flow. Improvements on this concept and design are confidently predicted and such devices should find wide application in pulsed laser operation.

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August 1976

APPENDIX A

```
).MAIN
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AMT(16,16), NN(16), SVR(16), TDIF(16), BMT(16)
      COMMON /VAR/ TO1G, TO2G, TO6G, TO7G, T1, T2, T3, T4, T6, T8,
     A  T10, T14, T16, T18, T20, TA2,
     B  TO3G, TO4G, TO5G, TO8G, TO9G, TO10G, TO11G, T5, T7, T9, T11,
     C  T12, T13, T15, T17, T19, TIG, T2G, T3G, T4G, T5G, T6G, T7G,
     D  T8G, T9G, T10G, T11G, TA1, EFFL, PO1G, PO2G, PO3G, PO4G, PO5G,
     E  PO6G, PO7G, PO8G, PO9G, PO10G, PO11G, PIG, P2G, P3G, P4G, P5G,
     F  P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
     G  FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
     H  GAMIG, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
     I  GAM10G, GAM11G, TGMI, TGMII, TMA, GIMU, GIIMU, AMU, PRGI,
     J  PRGII, PRA, CPGI, CPGII, CPA, TMI, TMII, TM, ZIMU, ZIIMU, ZMU,
     K  PRI, PRII, PR,  CPI, CPII, CP,  GGI, GGII, GA, GI, GII, G, REGI,
     L  REGII, REA, REI, REII, RE, GFI, GFII,  AF, FI, FII, F, GJI,
     M  GJII, AJ, ZJI, ZJII, ZJ, HGI, HGII, HA, HI, HII, H, CGI, CGII,
     N  CA, CI, CII, C, UI, UII, U, AGI, AGII, AA, TUNI, TUNII, TUN,
     O  TOWI, TOWII, TOW, EPSI, EPSII, EPSA, ESSI, ESSII, ESS, WG,
     P  Q6G, QCORR, BPR, ALT, PAT, PA2, RH, FN(4),      EFFLP, VI, VIM,
     Q  PIGA, H1M, CL1M, WT1M, DCM, BLPR, BLPRM, CPP, CPPM, PF, PFM,
     R          RO1, PLKW, WI, WII, WB, WM, WV1, WV2, WE, WS, WA, QP, QCM,
     S  QM, QV1, QV2, QE, QS, CF23, CF34, CF45, CF78, CF89, CF910
      COMMON /VAR/ CF111,      ATAP, H1, CL1, WT1, ACN(20), DC, DL(3),
     A  DH(3), DW(3), DDHG(3), DALG(3), DAFOA(3), DSIG(3), DDEL(3),
     B  DA(3), DK(3), DSL(3), DSI(3), DALF(3), DDH(3), CONV(16), DELM,
     C  ROLIM, PLIM, FG, TITLE(28), DP,  DPI, DPII, PPR, PPRM,
     D  TA1F, RHP, TIGM, DKH(3), ETIG,  ETO2G, ETO6G, ETO7G, ET1,
     E  ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET16, ET18, ET20, ETA2,
     F  EDPR, CWA, DNP(3), QDI, QDII, QDA, EVIM, BRPM, VLIM, ROA1,
     G  ROA2,DAFAL(3),DSLL(3),AB(3)
      COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLIM, NP(3), NFULL,
     1  NBS, NBPS, JCPRO
      EQUIVALENCE (SVR( 1),TO1G)

    2 CALL ENPUT
      T2G=TO2G
      T6G=TO6G
      T5G=TO2G
      T10G=TO7G
      JV=0
  501 II=0
      CALL GASP(TIG, FN, GAMIG, CPIG, Z1, Z1, GMU)
      IF (JCPRO .GE. 0)
     1  PIG=RO1*TIG/(.093178*GMU)
      IF (JCPRO .LT. 0)
     1  RO1=.093178*PIG*GMU/TIG
      WG=RO1*VI*A(1)
      FM1=WG*DSQRT(TIG/(GAMIG*GMU))/(20.7774*PIG*A(1))
      TO1G=TIG*(1.+FM1*FM1*(GAMIG-1.)/2.)
      T11G=TO1G
      WRITE(6,198)RO1,GMU,PIG,TIG
  198 FORMAT(1H0,3X,'RO1=',E15.7,5X,'GMU=',E15.7,5X,'PIG=',E15.7,
     1 5X,'TIG=',E15.7)
   10 DO 3 I=1,16
      DO 4 J=1,16
    4 AMT(I,J)=0.
```

AD-A041 040 ALABAMA UNIV IN HUNTSVILLE SCHOOL OF SCIENCE AND ENG--ETC F/G 20/5
INVESTIGATION OF TRANSIENT FLOW AND HEATING PROBLEMS CHARACTERI--ETC(U)
MAR 77 C C SHIH, G R KARR DAAK40-76-C-0474
UNCLASSIFIED UAH-RR-199 DRDMI-H-CR-77-9 NL

2 OF 2
AD A041040

END
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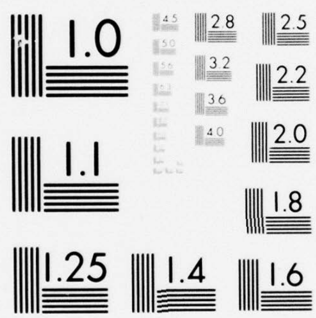
7-77


1.0
4.5
5.0
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

```
 3   BMT(I)=0.0
     WRITE(6,122) T02G
122  FORMAT(1H0,3X,'T02G=',E15.7)
     WRITE(6,121) T1,T2,T3,T4,T6,T8,T10,T14,T16,T18,T20
121  FORMAT(1H0,5X,'T1,T2,T3,T4,T6,T8,T10,T14,T16,T18,T20',/,3X,
    1 9E13.6,/,3X,2E13.6)
     TMI=.5*(T2+T4)
     TMII=.5*(T2+T6)
     TM=.5*(T3+T1)
     Z1=T5G-T4
     Z2=T6G-T2
     IF (Z1 .LE. 0.  .OR.  Z2 .LE. 0.)  GO TO 11
     IF (Z1 .EQ. Z2)  GO TO 12
     TGMI=TMI+(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
     GO TO 13
 11  TGMI=.5*(T5G+T6G)
     GO TO 13
 12  TGMI=.5*(T5G+T6G)
 13  Z1=T10G-T6
     Z2=T11G-T2
     IF (Z1 .LE. 0.  .OR.  Z2 .LE. 0.)  GO TO 14
     IF (Z1 .EQ. Z2)  GO TO 15
     TGMII=TMII+(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
     GO TO 16
 14  TGMII=.5*(T10G+T11G)
     GO TO 16
 15  TGMII=.5*(T10G+T11G)
 16  Z1= T1-TA1
     Z2=T3-TA2
     IF (Z1 .LE. 0.  .OR.  Z2 .LE. 0.)  GO TO 17
     IF (Z1 .EQ. Z2)  GO TO 18
     TMA=TM-(Z1-Z2)/(DLOG(Z1)-DLOG(Z2))
     GO TO 19
 17  TMA=.5*(TA1+TA2)
     GO TO 19
 18  TMA=.5*(TA1+TA2)
 19  CALL GASP(TGMI, FN, Z1, CPGI, PRGI, GIMU, GMU)
     CALL GASP(TGMII, FN, Z1, CPGII, PRGII, GIIMU, GMU)
     WRITE(6,199)GIMU,GIIMU,VI
199  FORMAT(1H0,3X,'GIMU=',E15.7,5X,'GIIMU=',E15.7,5X,'VI=',E15.7)
     CALL AIRP(TA1, PAT, TMA, RH, PRA, AMU, CPA, Z1, AML)
     CALL LIQP(TMI, FG, ZIMU, PRI, CPI)
     CALL LIQP(TMII, FG, ZIIMU, PRII, CPII)
     CALL LIQP(TM, FG, ZMU, PR, CP)
     AFRGI=DL(1)*DH(1)
     AFRGII=DL(2)*DH(2)
     AFRA=DL(3)*DH(3)
     GGI=WG/(DSIG(1)*AFRGI)
     GGII=WG/(DSIG(2)*AFRGII)
     GA=WA/(DSIG(3)*AFRA)
     AFRI=DW(1)*DH(1)/DNP(1)
     AFRII=DW(2)*DH(2)/DNP(2)
     AFR=DW(3)*DH(3)/DNP(3)
     GI=WI/(DSI(1)*AFRI)
     GII=WII/(DSI(2)*AFRII)
     W3=WI+WII+WB+WM+WV1+WV2+WE+WS
     G=W3/(DSI(3)*AFR)
```

```
      REGI=GGI*DDHG(1)/GIMU
      REGII=GGII*DDHG(2)/GIIMU
      REA=GA*DDHG(3)/AMU
      REI=GI*DDH(1)/ZIMU
      REII=GII*DDH(2)/ZIIMU
      RE=G*DDH(3)/ZMU
      WRITE(6,197)REGI,REGII,REA,REI,REII,RE
  197 FORMAT(1H0,3X,'REGI=',E13.6,4X,'REGII=',E13.6,4X,'REA=',E13.6,4X,
     1 'REI=',E13.6,4X,'REII=',E13.6,4X,'RE=',E13.6)
      Z1=DLOG(REGI)
      Z2=-750.2946+629.2028*Z1-219.5279*Z1**2+40.7569*Z1**3-4.253034*Z1*
     1*4+.2364432*Z1**5-.005466298*Z1**6
      GFI=DEXP(Z2)
      Z1=-360.4224+335.276*Z1-129.1436*Z1**2+26.20469*Z1**3-2.961196*Z1*
     1*4+.1766745*Z1**5-.004345743*Z1**6
      GJI=DEXP(Z1)
      Z1=DLOG(REGII)
      Z2=-750.2946+629.2028*Z1-219.5279*Z1**2+40.7569*Z1**3-4.253034*Z1*
     1*4+.2364432*Z1**5-.005466298*Z1**6
      GFII=DEXP(Z2)
      Z1=-360.4224+335.276*Z1-129.1436*Z1**2+26.20469*Z1**3-2.961196*Z1*
     1*4+.1766745*Z1**5-.004345743*Z1**6
      GJII=DEXP(Z1)
      Z1=DLOG(REA)
      Z2=-7.652462+6.206772*Z1-1.715187*Z1**2+.1756196*Z1**3-.006207806*
     1Z1**4
      AF=DEXP(Z2)
      Z1=2.123751-1.083736*Z1-.05205297*Z1**2+.01646661*Z1**3-.000782202
     11*Z1**4
      AJ=DEXP(Z1)
      Z1=DLOG(REI)
      Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
     11**4
      ZJI=DEXP(Z1)
      Z1=DLOG(REII)
      Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
     11**4
      ZJII=DEXP(Z1)
      Z1=DLOG(RE)
      Z1=-22.04452+12.84988*Z1-3.122052*Z1**2+.3159152*Z1**3-.01161237*Z
     11**4
      ZJ=DEXP(Z1)
      TO3=-2./3.
      HGI=GGI*CPGI*GJI*PRGI**TO3
      HGII=GGII*CPGII*GJII*PRGII**TO3
      HA=GA*CPA*AJ*PRA**TO3
      HI=GI*CPI*ZJI*PRI**TO3
      HII=GII*CPII*ZJII*PRII**TO3
      H=G*CP*ZJ*PR**TO3
      GMI=DSQRT(2.*HGI/(DK(1)*DDEL(1)))
      GMII=DSQRT(2.*HGII/(DK(2)*DDEL(2)))
      AM=DSQRT(2.*HA/(DK(3)*DDEL(3)))
      TO3=GMI*DSL(1)
      ATFI=DTANH(TO3)/TO3
      TO3=GMII*DSL(2)
      ATFII=DTANH(TO3)/TO3
      TO3=AM*DSL(3)
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```
      ATFA=DTANH(TO3)/TO3
      ATOI=1.-DAFOA(1)*(1.-ATFI)
      ATOII=1.-DAFOA(2)*(1.-ATFII)
      ATO=1.-DAFOA(3)*(1.-ATFA)
      GM1=DSQRT(2.*HI/(DK(1)*DA(1)))
      GM2=DSQRT(2.*HII/(DK(2)*DA(2)))
      AMN=DSQRT(2.*H/(DK(3)*DA(3)))
      TO3=GM1*DSLL(1)
      ATF1L=DTANH(TO3)/TO3
      TO3=GM2*DSLL(2)
      ATF2L=DTANH(TO3)/TO3
      TO3=AMN*DSLL(3)
      ATFAL=DTANH(TO3)/TO3
      ATO1=1.-DAFAL(1)*(1.-ATF1L)
      ATO2=1.-DAFAL(2)*(1.-ATF2L)
      ATOL=1.-DAFAL(3)*(1.-ATFAL)
      UI=1./(1./(ATOI*HGI) +AB(1)/(DK(1)*(1.-DAFOA(1))) +DALG(1)/(DALF(1
     1)*HI*ATO1))
      UII=1./(1./(ATOII*HGII)+AB(2)/(DK(2)*(1.-DAFOA(2)))+DALG(2)/(DALF(
     12)*HI*ATO2))
      U=1./(1./(ATO*HA)+AB(3)/(DK(3)*(1.-DAFOA(3)))+DALG(3)/(DALF(3)*HI*
     1ATOL))
      CGI=WG*CPGI
      CGII=WG*CPGII
      CA=WA*CPA
      CI=WI*CPI
      CII=WII*CPII
      C=W3*CP
      CMINI=DMIN1(CGI,CI)
      CMAXI=DMAX1(CGI,CI)
      CMINII=DMIN1(CGII,CII)
      CMAXII=DMAX1(CGII,CII)
      CMIN=DMIN1(CA,C)
      CMAX=DMAX1(CA,C)
      AGI=DL(1)*DH(1)*DW(1)*DALG(1)
      AGII=DL(2)*DH(2)*DW(2)*DALG(2)
      AA=DL(3)*DH(3)*DW(3)*DALG(3)
      TUNI=AGI*UI/CMINI
      TUNII=AGII*UII/CMINII
      TUN=AA*U/CMIN
      TOWI=1.-DEXP(-TUNI*CMINI/(CMAXI*DNP(1)))
      TOWII=1.-DEXP(-TUNII*CMINII/(CMAXII*DNP(2)))
      TOW=1.-DEXP(-TUN*CMIN/(CMAX*DNP(3)))
      ESSI=1.-DEXP(-TOWI*CMAXI/CMINI)
      ESSII=1.-DEXP(-TOWII*CMAXII/CMINII)
      ESS=1.-DEXP(-TOW*CMAX/CMIN)
      IF (CMINI/CMAXI .GT. .9999) GO TO 31
      EPSI=((1.-ESSI*CMINI/CMAXI)/(1.-ESSI))**NP(1)
      EPSI=(EPSI-1.)/(EPSI-CMINI/CMAXI)
      GO TO 32
   31 EPSI=DNP(1)*ESSI/(1.+ESSI*(DNP(1)-1.))
   32 IF (CMINII/CMAXII .GT. .9999)  GO TO 33
      EPSII=((1.-ESSII*CMINII/CMAXII)/(1.-ESSII))**NP(2)
      EPSII=(EPSII-1.)/(EPSII-CMINII/CMAXII)
      GO TO 34
   33 EPSII=DNP(2)*ESSII/(1.+ESSII*(DNP(2)-1.))
   34 IF (CMIN/CMAX .GT. .9999)  GO TO 35
```

```
      EPSA=((1.-ESS*CMIN/CMAX)/(1.-ESS))**NP(3)
      EPSA=(EPSA-1.)/(EPSA-CMIN/CMAX)
      GO TO 36
   35 EPSA=DNP(3)*ESS/(1.+ESS*(DNP(3)-1.))
   36 CONTINUE
      TO3=FM1*FM1
      PO1G=PIG*(1.+TO3*(GAMIG-1.)/2.)**(GAMIG/(GAMIG-1.))
      GO TO (30, 40, 50), NDSGN
C    CAVITY OPTION 1  CONST. MACH NUMBER
   30 FM2=FM1
      A(2)=A(1)*(TO2G/TO1G)**((1.+GAMIG*TO3)/2.)
      GO TO 60
C    CAVITY OPTION 2  CONST. AREA
   40 A(2)=A(1)
      Z1=TO1G*(1.+GAMIG*TO3)**2/(2.*(GAMIG+1.)*TO3*
     1  (1.+TO3*(GAMIG-1.)/2.))
      Z1=TO2G/Z1
      IF (Z1 .GT. 1.)  GO TO 10000
      I=0
12000 I=I+1
      CALL GASP(T2G , FN, GAM2G, CP2G, TO3, TO3, GMU)
      Z2 = 2.*GAM2G*Z1-2.*GAM2G-2.
      Z3=GAM2G*GAM2G*(Z1-1.)+1.
      IF (Z3 .NE. 0.)  GO TO 41
      FM2=DSQRT(-Z1/Z2)
      GO TO 60
   41 Z4=(-Z2+DSQRT(Z2*Z2-4.*Z1*Z3))/(2.*Z3)
      Z5=(-Z2-DSQRT(Z2*Z2-4.*Z1*Z3))/(2.*Z3)
      Z6=DMIN1(Z4, Z5)
      IF (Z6 .LT. 0.)  Z6=DMAX1(Z4, Z5)
      WRITE(6,174)TO2G,TO3,PR
  174 FORMAT(1H0,3X,'TO2G=',E15.7,5X,'TO3=',E15.7,5X,'PR=',E15.7)
      WRITE(6,173)Z1,Z2,Z3,Z4,Z5,Z6
  173 FORMAT(1H0,3X,'Z1=',E15.7,5X,'Z2=',E15.7,5X,'Z3=',E15.7,5X,
     1/,4X,'Z4=',E15.7,5X,'Z5=',E15.7,5X,'Z6=',E15.7)
      FM2=DSQRT(Z6)
      GO TO 60
C    CAVITY OPTION 3  GENERAL SHAPE
   50 Z5=(GAMIG+GAM2G)/2.
      Z6=FM1*FM1
      N=NCS-1
      DO 51 J=1,N
      Z1=-2.*(1.+Z6*(Z5-1.)/2.)/(1.-Z6)
      Z2=(1.+Z5*Z6)*(-.5*Z1)
      Z3=(ACN(J+1)-ACN(J))/(2.*(ACN(J+1)+ACN(J)))
      Z4=(TO2G-TO1G)/((NCS-1.)*TO1G-(J-.5)*(TO2G-TO1G))
      Z6=Z6*(1.+Z3*Z1+Z2*Z4)
      IF (Z6 .LE. 1.) GO TO 51
10000 WRITE(KO,105)
  105 FORMAT(41H**** CHOKED CAVITY - READ NEW DATA ******)
      GO TO 2
   51 CONTINUE
      FM2=DSQRT(Z6)
      A(2)=ACN(NCS)
   60 T2GOLD=T2G
      T2G=TO2G/(1.+FM2*FM2*(GAM2G-1.)/2.)
      T2GDIF=T2GOLD-T2G
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      IF(DABS(T2GDIF).LE..5D0) GO TO 11000
      IF(I.LE.NLIM) GO TO 12000
      PRINT 13000,I,T2GDIF
13000 FORMAT(58H****FAILURE TO CONVERGE IN STATIC TEMP. LOOP 1 - CYCLES
     '= ,I3,' - ERROR=',E12.5)
      GO TO 2
11000 P2G=WG*DSQRT(T2G/(GAM2G*GMU))/(20.7774*A(2)*FM2)
      P02G=P2G*(1.+FM2*FM2*(GAM2G-1.)/2.)**(GAM2G/(GAM2G-1.))
C    FIRST DIFFUSER
      P03G=P02G-CF23*(P02G-P2G)
      FM3=FM2*A(2)/A(3)
      GAM3G=GAM2G
      CALL MACH(DELM, NLIM, P03G, GAM3G, FM3, T02G, WG, GMU,
     1  A(3), P3G, T3G,FN,CP3G)
C    SECOND DIFFUSER
      P04G=P03G-CF34*(P03G-P3G)
      FM4=FM3*A(3)/A(4)
      GAM4G=GAM3G
      CALL MACH(DELM, NLIM, P04G, GAM4G, FM4, T02G, WG, GMU,
     1  A(4), P4G, T4G,FN,CP4G)
C    THIRD DIFFUSER
      P05G=P04G-CF45*(P04G-P4G)
      FM5=FM4*A(4)/A(5)
      GAM5G=GAM4G
      CALL MACH(DELM, NLIM, P05G, GAM5G, FM5, T02G, WG, GMU,
     1  A(5), P5G, T5G,FN,CP5G)
      R05=.093178*P5G*GMU/T5G
      R06=R05
      FM6=WG*DSQRT(T06G/GAM5G/GMU)/(20.7774*P05G*A(6))
      I=0
   70 Z1=R06
      P06G=P05G-GGI*GGI*((1.+DSIG(1)*DSIG(1))*(R05/R06-1.)+
     1  GFI*DALG(1)*DW(1)*R05/(.5*DSIG(1)*(R06+R05)))/
     2  (9266.11*R05)
      GAM6G=GAM5G
      CALL MACH(DELM,NLIM,P06G,GAM6G,FM6,T06G,WG,GMU,A(6),P6G,T6G,FN,
     *  CP6G)
      R06=.093178*P6G*GMU/T6G
      I=I+1
      Z3=R06-Z1
      IF (DABS(Z3) .LE. ROLIM) GO TO 71
      IF (I .LT. NLIM)  GO TO 70
      WRITE(K0,101) Z3
  101 FORMAT(53H**** FAILURE TO CONVERGE IN DENSITY LOOP 1 - ERROR = ,
     1  E12.5,6H******)
   71 CALL GASP(T07G, FN, GAM7G, CP7G, T03, T03, GMU)
      WRITE(K0,150) I, Z3
  150 FORMAT(10X,'DENSITY LOOP 1 - CYCLES =',I3,' - ERROR =',E12.5)
      P07G=P06G*BPR
      J=0
   80 FM7=WG*DSQRT(T07G/(GAM7G*GMU))/(20.7774*P07G*A(7))
      CALL MACH(DELM, NLIM, P07G, GAM7G, FM7, T07G, WG, GMU,
     1  A(7), P7G, T7G,FN,CP7G)
      FM8=FM7*A(7)/A(8)
      P08G=P07G-CF78*(P07G-P7G)
      GAM8G=GAM7G
      CALL MACH(DELM, NLIM, P08G, GAM8G, FM8, T07G, WG, GMU,
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    1  A(8), P8G, T8G,FN,CP8G)
      P09G=P08G-CF89*(P08G-P8G)
      FM9=FM8*A(8)/A(9)
      GAM9G=GAM8G
      CALL MACH(DELM, NLIM, P09G, GAM9G, FM9, T07G, WG, GMU,
    1  A(9), P9G, T9G,FN,CP9G)
      P010G=P09G-CF910*(P09G-P9G)
      FM10=FM9*A(9)/A(10)
      GAM10G=GAM9G
      CALL MACH(DELM, NLIM, P010G, GAM10G, FM10, T07G, WG, GMU,
    1  A(10), P10G, T10G,FN,CP10G)
      R010=.093178*P10G*GMU/T10G
      R011=R010
      FM11=WG*DSQRT(T011G/GAM10G/GMU)/(20.7774*P010G*A(10))
      I=0
   75 Z1=R011
      P011G=P010G-GGII*GGII*((1.+DSIG(2)*DSIG(2))*(R010/R011-1.)+
    1  GFII*DALG(2)*DW(2)*R010/(.5*DSIG(2)*(R010+R011)))/
    2  (9266.11*R010)
      GAM11G=GAM10G
      WRITE(6,183)P011G,GAM11G,FM11,T01G,WG
  183 FORMAT(1H0,3X,'P011G=',E15.7,5X,'GAM11G=',E15.7,5X,'FM11=',
    1 E15.7-5X,'T01G=',E15.7,5X,'WG=',E15.7)
      CALL MACH(DELM,NLIM,P011G,GAM11G,FM11,T01G,WG,GMU,A(10),P11G,
    * T11G,FN,CP11G)
      R011=.093178*P11G*GMU/T11G
      I=I+1
      Z3=R011-Z1
      IF (DABS(Z3) .LE. ROLIM)  GO TO 76
      IF (I .LT. NLIM)  GO TO 75
      WRITE(KO,120) Z3
  120 FORMAT(53H**** FAILURE TO CONVERGE IN DENSITY LOOP 2 - ERROR = ,
    1  E12.5,6H******)
   76 FM11=WG*DSQRT(T01G/(GAMIG*GMU))/(20.7774*P011G*A(11))
      WRITE(KO,151) I, Z3
  151 FORMAT(10X,'DENSITY LOOP 2 - CYCLES =',I3,' - ERROR =',E12.5)
      CALL MACH(DELM, NLIM, P011G,GAM11G ,FM11, T01G, WG, GMU,
    1  A(11), P11G, T11G,FN,CP11G)
      IF (JCPRO .GE. 0)
    1  Z1=R01*TIG/(.093178*GMU)*(1.+(GAMIG-1.)*FM1*FM1/2.)
    2     **(GAMIG/(GAMIG-1.))
      Z1=P011G-CF111*(P011G-P11G)-Z1
      IF (JCPRO .LT. 0)
    1  Z1=P011G-CF111*(P011G-P11G)-P01G
      P011G=P011G-Z1
      P010G=P010G-Z1
      P09G=P09G-Z1
      P08G=P08G-Z1
      P07G=P07G-Z1
      CALL GASP(T6G,FN, GAM6G, CP6G,Z2,Z2,GMU)
      BPR=P07G/P06G
      Q6G=60.*A(6)*FM6*DSQRT(GAM6G*T6G*32.174*1545.43/GMU)
      ATAB=.730-7.09843*(DABS(Q6G/BRPM/NBS-.5355))**2.08014
      ATAB=0.6
      WRITE(6,186)Z1,P07G,P06G,Q6G
  186 FORMAT(1H0,3X,'Z1=',E15.7,5X,'P07G=',E15.7,5X,'P06G=',E15.7,5X,
    1 'Q6G=',E15.7)
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      WRITE(6,187) T06G,BPR,GAM6G,ATAB
  187 FORMAT(1H0,3X,'T06G=',E15.7,5X,'BPR=',E15.7,5X,'GAM6G=',E15.7,5X,
     1 'ATAB=',E15.7)
      T07G=T06G*(BPR**((GAM6G-1.)/(ATAB*GAM6G)))
      WRITE(6,180) T06G,BPR,GAM6G,ATAB,T07G
  180 FORMAT(1H0,3X,'T06G=',E15.7,5X,'BPR=',E15.7,5X,'GAM6G=',E15.7,5X,
     1 'ATAB=',E15.7,5X,'T07G=',E15.7)
      J=J+1
      IF (DABS(Z1) .LT. PLIM)  GO TO 85
      IF (J .LT. NLIM)  GO TO 80
      WRITE(KO,103) Z1
  103 FORMAT(52H**** FAILURE TO CONVERGE IN PRESSURE LOOP - ERROR = ,
     1  E12.5,6H******)
   85 CALL AIRP(TA1, PAT, TA1, RH, Z2, Z2, CPA1, Z2, AML)
      WRITE(KO,152) J, Z1
  152 FORMAT(10X,'TOTAL PASSES THROUGH PRESSURE LOOP =',I3,
     1  ' - ERROR =',E12.5)
      CALL AIRP(TA1, PAT, TA2, RH, Z1,Z1, CPA2, GAM2A, AML)
      CALL LIQP(T1, FG, Z1, Z1, CP1)
      CALL LIQP(T2, FG, Z1, Z1, CP2)
      CALL LIQP(T3, FG, Z1, Z1, CP3)
      CALL LIQP(T4, FG, Z1, Z1, CP4)
      CALL LIQP(T6, FG, Z1, Z1, CP6)
      CALL LIQP(T8, FG, Z1, Z1, CP8)
      CALL LIQP(T10, FG,Z1, Z1, CP10)
      CALL LIQP(T14, FG,Z1, Z1, CP14)
      CALL LIQP(T16, FG,Z1, Z1, CP16)
      CALL LIQP(T18, FG,Z1, Z1, CP18)
      CALL LIQP(T20, FG,Z1, Z1, CP20)
      AMT( 1, 1)=WG*(CPIG+CP2G)/2.
      AMT( 1, 2)=-AMT(1,1)
      BMT( 1)=QS-.948*PLKW*(1./EFFL-1.)
      AMT(2,2)=CGI
      AMT(2,3)=-AMT(2,2)
      AMT(2,6)=WI*.5*(CP2+CP4)
      AMT(2,8)=-AMT(2,6)
      AMT(3,2)=EPSI*CMINI-CGI
      AMT(3,6)=-EPSI*CMINI
      AMT(3,3)= CGI
      AMT(4,4)=1.
      AMT(4,3)=-(P07G/P06G)**((GAM6G-1.)/(ATAB*GAM6G))
      AMT(5,4)=CGII
      AMT(5,1)=-AMT(5,4)
      AMT(5,6)=WII*.5*(CP2+CP6)
      AMT(5,9)=-AMT(5,6)
      AMT(6,4)=EPSII*CMINII-CGII
      AMT( 6, 6)=-EPSII*CMINII
      AMT(6,1)=CGII
      AMT(7,7)=W3*.5*(CP1+CP3)
      AMT(7,5)=-AMT(7,7)
      AMT(7,16)=-CA
      BMT(7)=AMT(7,16)*TA1
      AMT( 8, 7)=EPSA*CMIN
      AMT(8,16)=-CA
      BMT(8)=(EPSA*CMIN-CA)*TA1
      AMT(9,5)=W3*.5*(CP1+CP2)
      AMT(9,6)=-AMT(9,5)
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      BMT(9)=-QP
      AMT(10,8)=-WI*.5*(CP4+CP3)
      AMT(10,9)=-WII*.5*(CP6+CP3)
      AMT(10,13)=-WM*.5*(CP16+CP3)
      AMT(10,6)=-WB*.5*(CP2+CP3)
      AMT(10,10)=-WV1*.5*(CP8+CP3)
      AMT(10,11)=-WV2*.5*(CP10+CP3)
      AMT(10,14)=-WE*.5*(CP18+CP3)
      AMT(10,15)=-WS*.5*(CP20+CP3)
      AMT(10,7)=-AMT(10,8)-AMT(10,9)-AMT(10,13)-AMT(10,6)-AMT(10,10)-
     * AMT(10,11)-AMT(10,14)-AMT(10,15)
      AMT(11,6)=WM*.5*(CP2+CP14)
      AMT(11,12)=-AMT(11,6)
      BMT(11)=-QCM
      AMT(12,12)=WM*.5*(CP14+CP16)
      AMT(12,13)=-AMT(12,12)
      BMT(12)=-QM
      AMT(13,6)=WV1*.5*(CP2+CP8)
      AMT(13,10)=-AMT(13,6)
      BMT(13)=-QV1
      AMT(14,6)=WV2*.5*(CP2+CP10)
      AMT(14,11)=-AMT(14,6)
      BMT(14)=-QV2
      AMT(15,6)=WE*.5*(CP2+CP18)
      AMT(15,14)=-AMT(15,6)
      BMT(15)=-QE
      AMT(16,6)=WS*.5*(CP2+CP20)
      AMT(16,15)=-AMT(16,6)
      BMT(16)=-QS
      CALL SIMQ(AMT, BMT, 16, KS)
      WRITE(6,122) TO2G
      JJ=0
    6 Z2=FM1
      TIG=BMT(1)/(1.+(GAMIG-1.)*FM1*FM1/2.)
      CALL GASP(TIG, FN, GAMIG, CPIG, Z1, Z1, GMU)
      IF (JCPRO .GE. 0)
     1  PIG=RO1*TIG/(.093178*GMU)
      IF (JCPRO .LT. 0)
     1  RO1=.093178*PIG*GMU/TIG
      WG=RO1*VI*A(1)
      WRITE(6,160)TIG,GAMIG,GMU,WG
  160 FORMAT(1H0,3X,'TIG=',E14.6,5X,'GAMIG=',E14.6,5X,'GMU=',E14.6,5X,
     1 'WG=',E14.6)
      WRITE(6,162)
  162 FORMAT(1H0,8X,'SVR',16X,'BMT')
      WRITE(6,161)(SVR(MP),BMT(MP),MP=1,16)
  161 FORMAT(3X,E14.6,5X,E14.6)
      FM1=WG*DSQRT(TIG/(GAMIG*GMU))/(20.7774*PIG*A(1))
      JJ=JJ+1
      Z3=Z2-FM1
      IF (DABS(Z3) .LT. DELM)  GO TO 7
      IF (JJ .LT.NLIM)  GO TO 6
      WRITE(KO,400) Z3
  400 FORMAT(54H**** FAILURE TO CONVERGE IN FINAL MACH LOOP - ERROR = ,
     1  E12.5,6H******)
    7 WRITE(KO,301) JJ, Z3
  301 FORMAT(10X,'TOTAL PASSES IN FINAL MACH LOOP =',I3,' - ERROR =',
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    1  E12.5)
      II=II+1
      IF (KS .EQ. 1)  GO TO 91
      DO 93 KS=1,16
      NN(KS)=-1
      TDIF(KS)=SVR(KS)-BMT(KS)
      IF  (DABS(TDIF(KS)) .GT. CONV(KS))  NN(KS)=1
   93 CONTINUE
      WRITE(KO,201)
  201 FORMAT(10X,'STATE VARIABLE ERRORS')
      WRITE(KO,300) TDIF
  300 FORMAT(10X,10E12.4)
      WRITE(KO,153) II
  153 FORMAT(10X,'END OF SIMQ PASS NO.',I3/)
      IF (II .GT. NLIM)  GO TO 92
      DO 94 KS=1,16
      IF (NN(KS) .GE. 0)  GO TO 95
   94 CONTINUE
      GO TO 90
   92 WRITE(KO,104)
  104 FORMAT(48H**** FAILURE TO CONVERGE IN STATE VARIABLE LOOP*,
    1 6H******)
   90 FM6=WG*DSQRT(T06G/(GAM6G*GMU))/(20.7774*P06G*A(6))
      CALL MACH(DELM, NLIM, P06G, GAM6G, FM6, T06G, WG, GMU,
    1  A(6), P6G, T6G,FN,CP6G)
      FNBPS=DFLOAT(NBPS)
      FNBS=DFLOAT(NBS)
      DPSS=((P07G-P06G)*T06G*28.966)/(P06G*BRPM*BRPM*518.7*GMU*FNBPS)
      DPSB=.8396-3.2323*(DABS(Q6G/(BRPM*FNBS)-.46875))**1.42327
      DPSB=DPSB*1.E-9
      ERR=DPSB-DPSS
      GC=11.661E-7/(BRPM*FNBS)+11.589E-5*VIM**.667/(BRPM*BRPM*FNBPS)
      GC=ERR/GC
      JV=JV+1
      WRITE(KO,204)  JV, GC
  204 FORMAT(5X,'PASS NO.',I3,' THROUGH VELOCITY LOOP,  CORRECTION =',
    1  E12.5)
      WRITE(6,175)Q6G,BRPM,FNBS
  175 FORMAT(1H0,3X,'Q6G=',E15.7,5X,'BRPM=',E15.7,5X,'FNBS=',E15.7)
      GC=0.0
      IF (DABS(GC) .LE. VLIM)  GO TO 502
      IF (JV .GE. NLIM) GO TO 503
      GO TO 506
      IF (GC .LT. 0.  .AND. Q6G/(BRPM*FNBS) .LT. .46875)  GO TO 504
  506 CONTINUE
      VIM=VIM+GC
      VI=VIM*3.281
      GO TO 501
  504 WRITE(KO,205)
  205 FORMAT(50H**** BLOWERS ARE CHOKED - PROCESS NEXT CASE ******)
      GO TO 2
  503 WRITE(KO,203) GC
  203 FORMAT(52H**** FAILURE TO CONVERGE IN VELOCITY LOOP - ERROR = ,
    1  E12.5,6H******)
  502 CONTINUE
      T03G=T02G
      T04G=T02G
```

```
      T05G=T02G
      T08G=T07G
      T09G=T07G
      T010G=T07G
      T011G=T01G
      BLPR=WG*.5*(CP6G+CP7G)*T06G*(BPP**((1.-2./(GAM6G+GAM7G))
     1  /ATAB)-1.)*778./550.
      BLPRM=BLPR*.7457
      DPI=4.317E-4*GI*GI*FI*DL(1)*DNP(1)/(ROLI*DDH(1))
      DPII=4.317E-4*GII*GII*FII*DL(2)*DNP(2)/(ROLII*DDH(2))
      DP=4.317E-4*G*G*F*DL(3)*DNP(3)/(ROL*DDH(3))
      ROA1=144.*PAT*AML/(1545.32*TA1)
      ROA2=ROA1
      LL=0
   37 Z1=ROA2
      PA2=PAT-GA*GA*((1.+DSIG(3)**2)*(ROA1/ROA2-1.)+
     1  AF*DALG(3)*DW(3)*ROA1/(.5*DSIG(3)*(ROA1+ROA2)))/
     2  (ROA1*2.*32.174*144.)
      ROA2=144.*PA2*AML/(1545.32*TA2)
      LL=LL+1
      Z3=ROA2-Z1
      IF  (DABS(Z3) .LT. ROLIM) GO TO 38
      IF  (LL .LE. NLIM)  GO TO 37
      WRITE(KO,401) Z3
  401 FORMAT(49H**** FAILURE TO CONVERGE IN AUX. DENSITY LOOP - *,
     1  'ERROR =',E12.5,6H******)
      GO TO 39
   38 WRITE(KO,202) LL, Z3
  202 FORMAT(10X,'TOTAL PASSES THROUGH AUX. DENSITY LOOP =',I3,
     1  ' - ERROR =',E12.5)
   39 PF=WA*CPA2*TA2*((PAT/PA2)**((1.-1./GAM2A)/ATAP)-1.)*778./550.
      PFM=.7457*PF
      R06G=.093178*P6G*GMU/T6G
      QCORR=60.*WG*DSQRT(1.4*GMU*518.7/(GAM6G*28.97*T06G))/R06G
      DO 99 KS=1,16
   99 SVR(KS)=BMT(KS)
      QDI=WI*1800.*(CP2+CP4)*(T4-T2)
      QDII=WII*1800.*(CP2+CP6)*(T6-T2)
      QDA=W3*1800.*(CP3+CP1)*(T3-T1)
      CALL OUTPUT
      GO TO 2
   95 DO 96 KS=1,16
   96 SVR(KS)=BMT(KS)
      GO TO 10
   91 WRITE(KO,102)
  102 FORMAT(' SINGULAR MATRIX')
      GO TO 2
      END
```

ENPUT

```
).ENPUT
      SUBROUTINE ENPUT
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION SVR(19)
      DIMENSION ESVR(16)
      COMMON /VAR/ TO1G, TO2G, TO6G, TO7G, T1, T2, T3, T4, T6, T8,
     A  T10, T14, T16, T18, T20, TA2,
     B  TO3G, TO4G, TO5G, TO8G, TO9G, TO10G, TO11G, T5, T7, T9, T11,
     C  T12, T13, T15, T17, T19, TIG, T2G, T3G, T4G, T5G, T6G, T7G,
     D  T8G, T9G, T10G, T11G, TA1, EFFL, PO1G, PO2G, PO3G, PO4G, PO5G,
     E  PO6G, PO7G, PO8G, PO9G, PO10G, PO11G, PIG, P2G, P3G, P4G, P5G,
     F  P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
     G  FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
     H  GAMIG, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
     I  GAM10G, GAM11G, TGMI, TGMII, TMA, GIMU, GIIMU, AMU, PRGI,
     J  PRGII, PRA, CPGI, CPGII, CPA, TMI, TMII, TM, ZIMU, ZIIMU, ZMU,
     K  PRI, PRII, PR, CPI, CPII, CP, GGI, GGII, GA, GI, GII, G, REGI,
     L  REGII, REA, REI, REII, RE, GFI, GFII, AF, FI, FII, F, GJI,
     M  GJII, AJ, ZJI, ZJII, ZJ, HGI, HGII, HA, HI, HII, H, CGI, CGII,
     N  CA, CI, CII, C, UI, UII, U, AGI, AGII, AA, TUNI, TUNII, TUN,
     O  TOWI, TOWII, TOW, EPSI, EPSII, EPSA, ESSI, ESSII, ESS, WG,
     P  Q6G, QCORR, BPR, ALT, PAT, PA2, RH, FN(4),      EFFLP, VI, VIM,
     Q  PIGA, H1M, CL1M, WT1M, DCM, BLPR, BLPRM, CPP, CPPM, PF, PFM,
     R         RO1, PLKW, WI, WII, WB, WM, WV1, WV2, WE, WS, WA, QP, QCM,
     S  QM, QV1, QV2, QE, QS, CF23, CF34, CF45, CF78, CF89, CF910,
      COMMON /VAR/ CF111,       ATAP, H1, CL1, WT1, ACN(20), DC, DL(3),
     A  DH(3), DW(3), DDHG(3), DALG(3), DAFOA(3), DSIG(3), DDEL(3),
     B  DA(3), DK(3), DSL(3), DSI(3), DALF(3), DDH(3), CONV(16), DELM,
     C  ROLIM, PLIM, FG, TITLE(28), DP,  DPI, DPII, PPR, PPRM,
     D  TA1F, RHP, TIGM, DKH(3), ETIG, ETO2G, ETO6G, ETO7G, ET1,
     E  ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET16, ET18, ET20, ETA2,
     F  EBPR, CWA, DNP(3), QDI, QDII, QDA, EVIM, BRPM, VLIM, ROA1,
     G  ROA2,DAFAL(3),DSLL(3),AB(3)
      COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLIM, NP(3), NFULL,
     1  NBS, NBPS, JCPRO

      EQUIVALENCE (ESVR(1), ETIG)
      EQUIVALENCE (SVR(1),TO1G)
      NAMELIST/FPT/ NTAM, TA1F, PLKW, ETIG, ETO2G, ETO6G, ETO7G, ET1,
     A  ET2, ET3, ET4, ET6, ETA2, ET14, ET16, ET8, ET10, ET18, ET20,
     B                     EFFLP, WI, WII, WB, WM, WV1, WV2, WE, WS, CWA,
     C                    QP, QCM, QM, QV1, QV2, QE, QS, CF23, CF34,
     D  CF45, CF78, CF89, CF910, CF111,
     E                  EVIM, ATAP, PIGA, H1M, CL1M, WT1M, FN, ACN, DCM,
     F                    DL, DH, DW, DDHG, DALG, DAFOA, DSIG, DDEL,
     G  DA, DKH, DSL, DSI, DALF, DDH, NP,
     H                     PAT, RHP, EBPR, A, CONV, DELM, NDSGN, NCS,
     I       NLIM, ROLIM, PLIM, FG, BRPM, VLIM, NBS, NBPS, JCPRO, RO1,
     J  DAFAL,DSLL, AB

      KI=5
      KO=6
      READ(KI,200) (TITLE(J),J=1,14)
      READ(KI,200) (TITLE(J),J=15,28)
  200 FORMAT(13A6,A2)
      READ(KI,FPT)
      TA1=TA1F+459.69
```

```
      TIG=TA1+20.
      TO2G=TA1+210.
      TO6G=TA1+30.
      TO7G=TA1+70.
      T1=TA1+20.
      T2=TA1+20.
      T3=TA1+40.
      T4=TA1+55.
      T6=TA1+30.
      T8=TA1+65.
      T10=TA1+65.
      T14=TA1+30.
      T16=TA1+75.
      T18=TA1+65.
      T20=TA1+65.
      TA2=TA1+30.
      BPR=1.17
      VIM=120.
      DO 30 K=1,16
   30 IF (ESVR(K) .GT. 0.)  SVR(K)=ESVR(K)
      IF (EBPR .GT. 0.)  BPR=EBPR
      IF (EVIM .GT. 0.)  VIM=EVIM
      IF (NTAM .LT. 0)  CALL EXIT
      IF (NTAM .LE. 0)  GO TO 10
      DO 20 J=1,19
   20 SVR(J)=TA1
   10 CONTINUE
      PIG=PIGA*14.7
      RH=RHP*.01
      EFFL=EFFLP*.01
      VI=VIM*3.281
      DC=DCM*.03281
      H1=H1M*.03281
      WT1=WT1M*.03281
      CL1=CL1M*.03281
      CALL AIRP(TA1, PAT, TA1, RH, X, X, X, X, AML)
      ROA1=PAT*AML*.09317/TA1
      WA=ROA1*CWA*DSQRT(TA1/518.7)/60.
      DK(1) = DKH(1)/3600.
      DK(2) = DKH(2)/3600.
      DK(3) = DKH(3)/3600.
      DNP(1)=NP(1)
      DNP(2)=NP(2)
      DNP(3)=NP(3)
      A(1)=H1*CL1
      Q6G=VI*A(1)*60.
      WRITE(KO,102)
  102 FORMAT('1')
      WRITE(KO,FPT)
  101 FORMAT(21X,14A6)
      WRITE(KO,101) TITLE
      RETURN
      END
```

```
.GASP
      SUBROUTINE GASP(T, FN, GAM, CP, PR, UM, GMU )
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION FN(4), WM(4), TB(4), C(4), U(4), FK(4),
     1 G(4), X(4), CN(4), S(4)
C     1 = HE
C     2 = N2
C     3 = CO2
C     4 = CO
      DATA TB /4.215D0,77.4D0,194.66D0,81.5D0/
      DATA WM /4.00D0,28.016D0, 44.010D0, 28.010D0/ , R /1.98646D0/

      C(1) = 1.2406

      IF (T .LE. 650.)
     1 FK(1)=(.8+(T-475.)*(.97-.8)/175.)*.1
      IF (T .GT. 650.)
     1 FK(1)=(.97+(T-650.)*(1.13-.97)/200.)*.1
      FK(1)=FK(1)/3600.

      G(1)=1.6667

      U(1)=1.12+(T-400.)*(1.955-1.12)/500.
      U(1)=U(1)*1.E-5


      IF (T .LE. 600)
     1 C(2)=3.502+(T-400.)*(3.5065-3.502)/200.
      IF (T .GT. 600.   .AND.   T .LE. 800.)
     1 C(2)=3.5065+(T-600.)*(3.5315-3.5065)/200.
      IF (T .GT. 800.)
     1 C(2)=3.5315+(T-800.)*(3.559-3.5315)/100.
      C(2)=C(2)*R/WM(2)

      IF (T .LE. 650.)
     1 FK(2)=.925+(T-450.)*(1.265-.925)/200.
      IF (T .GT. 650.)
     1 FK(2)=1.265+(T-650.)*(1.573-1.265)/200.
      FK(2)=FK(2)*1.4E-2/3600.

      G(2)=1.4
      IF (T .GT. 600.)
     1 G(2)=1.4+(T-600.)*(1.391-1.4)/300.

      IF (T .LE. 550.)
     1 U(2)=.933+(T-450.)*(1.087-.933)/100.
      IF (T .GT. 550.   .AND.   T .LE. 725.)
     1 U(2)=1.087+(T-550.)*(1.33-1.087)/175.
      IF (T .GT. 725)
     1 U(2)=1.33+(T-725.)*(1.545-1.33)/175.
      U(2)=U(2)*1.1172E-5


      IF (T .LE. 600.)
     1 C(3)=4.195+(T-450.)*(4.653-4.195)/150.
      IF (T .GT. 600.   .AND.   T .LE. 750.)
     1 C(3)=4.653+(T-600.)*(5.045-4.653)/150.
```

```
      IF (T .GT. 750.)
     1  C(3)=5.045+(T-750.)*(5.365-5.045)/150.
      C(3)=C(3)*R/WM(3)

      IF (T .LE. 600.)
     1  FK(3)=.82+(T-425.)*(1.32-.82)/175.
      IF(T.LE.140.)FK(3)=5.714E-3
      IF (T .GT. 600.)
     1  FK(3)=1.32+(T-600.)*(2.12-1.32)/250.
      FK(3)=FK(3)*8.407E-3/3600.

      IF (T .LE. 450.)
     1  G(3)=1.334+(T-400.)*(1.315-1.334)/50.
      IF (T .GT. 450.  .AND.  T .LE. 550.)
     1  G(3)=1.315+(T-450.)*(1.286-1.315)/100.
      IF (T .GT. 550.  .AND.  T .LE. 650.)
     1  G(3)=1.286+(T-550.)*(1.2645-1.286)/100.
      IF (T .GT. 650.  .AND.  T .LE. 750.)
     1  G(3)=1.2645+(T-650.)*(1.248-1.2645)/100.
      IF (T .GT. 750.  .AND.  T .LE. 850.)
     1  G(3)=1.248+(T-750.)*(1.235-1.248)/100.
      IF (T .GT. 850.)
     1  G(3)=1.235+(T-850.)*(1.2295-1.235)/50.

      IF (T .LE. 575.)
     1  U(3)=.9175+(T-450.)*(1.152-.9175)/125.
      IF (T .GT. 575.  .AND.  T .LE. 700.)
     1  U(3)=1.152+(T-575.)*(1.375-1.152)/125.
      IF (T .GT. 700.)
     1  U(3)=1.375+(T-700.)*(1.541-1.375)/100.
      U(3)=U(3)*9.2067E-6

      FT=FN(1)+FN(2)+FN(3)
      NGAS=3
      IF (FN(4) .LE. 0.)  GO TO 10
      FT=FT+FN(4)
      NGAS=4

      IF (T .LE. 540.)
     1  C(4)=3.503+(T-400.)*(3.506-3.503)/140.
      IF (T .GT. 540.  .AND.  T .LE. 630.)
     1  C(4)=3.506+(T-540.)*(3.513-3.506)/90.
      IF (T .GT. 630.  .AND.  T .LE. 720.)
     1  C(4)=3.513+(T-630.)*(3.529-3.513)/90.
      IF (T .GT. 720.  .AND.  T .LE. 810.)
     1  C(4)=3.529+(T-720.)*(3.552-3.529)/90.
      IF (T .GT. 810.)
     1  C(4)=3.552+(T-810.)*(3.583-3.552)/90.
      C(4)=C(4)*.0708989

      IF (T .LE. 540.)
     1  U(4)=.84+(T-400.)*(1.075-.84)/140.
      IF (T .GT. 540.  .AND.  T .LE. 720.)
     1  U(4)=1.075+(T-540.)*(1.34-1.075)/180.
      IF (T .GT. 720.)
     1  U(4)=1.34+(T-720.)*(1.575-1.34)/180.
      U(4)=U(4)*1.1132E-5
```

```
      IF (T .LE. 530.)
     1  G(4)=1.4
      IF (T .GT. 530.)
     1  G(4)=1.4+(T-530.)*(1.3885-1.4)/370.

      IF (T .LE. 540.)
     1  FK(4)=.825+(T-400.)*(1.087-.825)/140.
      IF (T .GT. 540.  .AND.  T .LE. 720.)
     1  FK(4)=1.087+(T-540.)*(1.385-1.087)/180.
      IF (T .GT. 720.)
     1  FK(4)=1.385+(T-720.)*(1.665-1.385)/180.
      FK(4)=FK(4)*.01342/3600.


0     CP=0.
      DAM=0.
      GAM=0.
      UM=0.
      GMU=0.
      Z3=0.
      DO 11 I=1,NGAS
      S(I)=1.5*TB(I)*1.8
      X(I)=FN(I)/FT
1     GMU=GMU+X(I)*WM(I)
      DO 50 I=1,NGAS
      CN(I)=X(I)*WM(I)/GMU
      CP=CP+CN(I)*C(I)
      GAM=CN(I)*C(I)+GAM
      DAM=CN(I)*C(I)/G(I)+DAM
      Z1=0.
      Z2=0.
      DO 30 J=1,NGAS
      IF (J .NE. I)  GO TO 12
      P=1.
      AM=1.
      GO TO 29
2     D=X(J)/X(I)
      E=DSQRT(S(I)*S(J))
      UR=U(I)/U(J)
      WR1=DSQRT(8.*(1.+WM(I)/WM(J)))
      WR=(WM(J)/WM(I))**.25
      P=D*(1.+DSQRT(UR)*WR)**2/WR1
      AM=.25*D*(1.+DSQRT(UR*WR**3*(T+S(I))/(T+S(J))))**2*(T+E)/(T+S
9     Z1=Z1+P
      Z2=Z2+AM
0     CONTINUE
      Z3=Z3+FK(I)/Z2
      UM=UM+U(I)/Z1
0     CONTINUE
      GAM=GAM/DAM
      PR=CP*UM/Z3
      RETURN
      END


RP
```

AIRP

```
      SUBROUTINE AIRP(TAMB, PAMB, T, RH, P, AMU, CPA, GAM, AML)
      IMPLICIT REAL*8 (A-H,O-Z)
      T2=DEXP(-38.09873+.1057402*TAMB-.674864E-4*TAMB*TAMB)
      WF=RH*18.016*T2/(28.966*(PAMB-T2))
      T2=T*T
      P=.5552+.134633E-2*T-.031E-4*T2+.20666E-8*T*T2
      AMU=1.E-5+.175E-7*(T-400.)
      CPA=.2421-.0015E-2*T+2.E-8*T2
      GAMA=CPA/(CPA-.0685545)
      CPW=.4509-.0054E-2*T+.0008E-4*T2
      GAMW=CPW/(CPW-.11022)
      A=WF*CPW
      B=(1.-WF)*CPA
      CPA=WF*CPW+(1.-WF)*CPA
      GAM=(A+B)/(A/GAMW+B/GAMA)
      AML=18.016*WF+28.966*(1.-WF)
      RETURN
      END
```

CH

MACH

```
      SUBROUTINE MACH(DELM, NLIM, POG, GAM, FM, TOG, WG, GMU, A, PG,
     1 TG,FN,CP)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION FN(4)
      DATA KO /6/
      I=0
   10 FMG=FM
      TG=1.+FMG*FMG*(GAM-1.)/2.
      WRITE(6,11)POG,TG,GAM
   11 FORMAT(1H0,3X,'POG=',E15.7,5X,'TG=',E15.7,5X,'GAM=',E15.7)
      PG=POG/TG**(GAM/(GAM-1.))
      TG=TOG/TG
      FM=WG*DSQRT(TG/(GAM*GMU))/(20.7774*PG*A)
      WRITE(6,12)PG,TG,FM
   12 FORMAT(1H0,3X,'PG=',E15.7,5X,'TG=',E15.7,5X,'FM=',E15.7)
      CALL GASP(TG,FN,GAM,CP,DUM,DUM,GMU)
      I=I+1
      FMG1=FMG-FM
      IF (DABS(FMG1) .LT. DELM)  RETURN
      IF (I .LT. NLIM) GO TO 10
      WRITE(KO,100) FMG1
   00 FORMAT('        FAILURE TO CONVERGE IN MACH NO. SUBROUTINE',
     1  ' - ERROR =',F12.5)
      RETURN
      END
```

QP

LIQP

```
      SUBROUTINE LIQP(T, FG, UM, PR, CP)
      IMPLICIT REAL*8 (A-H,O-Z)
      C=T/1.8-273.
      F=FG*FG
      CP=1.-.465*FG+C*(.00115-.00105*(1.-FG)**3.0596)
      SF=1301./(998.33+8.1855*(C-20.)+.00585*(C-20.)**2)
      UM=DEXP(-3.01174+.49287*FG+(2.30854+1.18556*FG+.806*F)*SF)
      FK=137.-82.91667*FG+17.91667*F
      FK=1.*(FK+C*(166.-160.8833*FG+49.0833*F-FK)/100.)
      UM=0.014881
      PR = 1.0E3*UM*CP/FK
      UM=UM*.000672
      RETURN
      END
```

MG

```
SIMQ
      SUBROUTINE SIMQ(A, B, N, KS)
      IMPLICIT REAL*8 (A-H,O-Z)

      SIMQ SOLVES A SYSTEM OF LINEAR EQUATIONS  AX=B

      INPUTS
      A - MATRIX OF COEFFICIENTS STORED COLUMNWISE. DESTROYED IN
          COMPUTATION
      B - VECTOR OF ORIGINAL CONSTANTS. DESTROYED IN COMPUTATION
          SOLUTION IS RETURNED IN B
      N - NUMBER OF EQUATIONS AND VARIABLES
      KS - OUTPUT FLAG  0=NORMAL   1=SINGULAR SET OF EQUATIONS

      DIMENSION A(1), B(1)

      FORWARD SOLUTION

      TOL=0.0
      KS=0
      JJ=-N
      DO 65 J=1,N
      JY=J+1
      JJ=JJ+N+1
      BIGA=0.0
      IT=JJ-J
      DO 30 I=J,N

      SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN

      IJ=IT+I
      IF (DABS(BIGA)-DABS(A(IJ))) 20,30,30
   20 BIGA=A(IJ)
      IMAX=I
   30 CONTINUE

      TEST FOR PIVOT LESS THAN TOLERANCE (SINGULAR MATRIX)

      IF (DABS(BIGA)-TOL) 35, 35, 40
   35 KS=1
      RETURN

      INTERCHANGE ROWS IF NECESSARY

   40 I1=J+N*(J-2)
      IT=IMAX-J
      DO 50 K=J,N
      I1=I1+N
      I2=I1+IT
      SAVE=A(I1)
      A(I1)=A(I2)
      A(I2)=SAVE

      DIVIDE EQUATION BY LEADING COEFFICIENT

   50 A(I1)=A(I1)/BIGA
      SAVE=B(IMAX)
```

```
      B(IMAX)=B(J)
      B(J)=SAVE/BIGA

      ELIMINATE NEXT VARIABLE

      IF (J-N) 55, 70, 55
   55 IQS=N*(J-1)
      DO 65 IX=JY,N
      IXJ=IQS+IX
      IT=J-IX
      DO 60 JX=JY,N
      IXJX=N*(JX-1)+IX
      JJX=IXJX+IT
   60 A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))
   65 B(IX)=B(IX)-(B(J)*A(IXJ))

      BACK SOLUTION

   70 NY=N-1
      IT=N*N
      DO 80 J=1,NY
      IA=IT-J
      IB=N-J
      IC=N
      DO 80 K=1,J
      B(IB)=B(IB)-A(IA)*B(IC)
      IA=IA-N
   80 IC=IC-1
      RETURN
      END

   TPUT
```

```
.OUTPUT
      SUBROUTINE OUTPUT
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION VG(11), QG(11), QC(20), QCG(20), DPC(20), DPCR(20)
      DIMENSION PDG(11), PP(11), PC(20), PD(11), ROG(11)
      COMMON /VAR/ TO1G, TO2G, TO6G, TO7G, T1, T2, T3, T4, T6, T8,
     A  T10, T14, T16, T18, T20, TA2,
     B  TO3G, TO4G, TO5G, TO8G, TO9G, TO10G, TO11G, T5, T7, T9, T11,
     C  T12, T13, T15, T17, T19, TIG, T2G, T3G, T4G, T5G, T6G, T7G,
     D  T8G, T9G, T10G, T11G, TA1, EFFL, PO1G, PO2G, PO3G, PO4G, PO5G,
     E  PO6G, PO7G, PO8G, PO9G, PO10G, PO11G, PIG, P2G, P3G, P4G, P5G,
     F  P6G, P7G, P8G, P9G, P10G, P11G, P(20), AC(20), VC(20), FM1,
     G  FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10, FM11, A(11),
     H  GAMIG, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G, GAM8G, GAM9G,
     I  GAM10G, GAM11G, TGMI, TGMII, TMA, GIMU, GIIMU, AMU, PRGI,
     J  PRGII, PRA, CPGI, CPGII, CPA, TMI, TMII, TM, ZIMU, ZIIMU, ZMU,
     K  PRI, PRII, PR, CPI, CPII, CP, GGI, GGII, GA, GI, GII, G, REGI,
     L  REGII, REA, REI, REII, RE, GFI, GFII, AF, FI, FII, F, GJI,
     M  GJII, AJ, ZJI, ZJII, ZJ, HGI, HGII, HA, HI, HII, H, CGI, CGII,
     N  CA, CI, CII, C, UI, UII, U, AGI, AGII, AA, TUNI, TUNII, TUN,
     O  TOWI, TOWII, TOW, EPSI, EPSII, EPSA, ESSI, ESSII, ESS, WG,
     P  Q6G, QCORR, BPR, ALT, PAT, PA2, RH, FN(4),       EFFLP, VI, VIM,
     Q  PIGA, H1M, CL1M, WT1M, DCM, BLPR, BLPRM, CPP, CPPM, PF, PFM,
     R          RO1, PLKW, WI, WII, WB, WM, WV1, WV2, WE, WS, WA, QP, QCM,
     S  QM, QV1, QV2, QE, QS, CF23, CF34, CF45, CF78, CF89, CF910,
      COMMON /VAR/ CF111,      ATAP, H1, CL1, WT1, ACN(20), DC, DL(3),
     A  DH(3), DW(3), DDHG(3), DALG(3), DAFOA(3), DSIG(3), DDEL(3),
     B  DA(3), DK(3), DSL(3), DSI(3), DALF(3), DDH(3), CONV(16), DELM,
     C  ROLIM, PLIM, FG, TITLE(28), DP,  DPI, DPII, PPR, PPRM,
     D  TA1F, RHP, TIGM, DKH(3), ETIG, ETO2G, ETO6G, ETO7G, ET1,
     E  ET2, ET3, ET4, ET6, ET8, ET10, ET14, ET16, ET18, ET20, ETA2,
     F  EBPR, CWA, DNP(3), QDI, QDII, QDA, EVIM, RRPM, VLIM, ROA1,
     G  ROA2,DAFAL(3),DSLL(3),AB(3)
      COMMON /IVAR/ NTAM, NDSGN, NCS, KI, KO, NLIM, NP(3), NFULL,
     1  NBS, NBPS, JCPRO
      WRITE(KO,100)
      WRITE(KO,101) TITLE
      WRITE(KO,400)
  400 FORMAT('0     INPUT LIST'/' CAVITY * LASER SPECIFICATIONS'/
     1 '             DESCRIPTION',24X,' NAME     VALUE        UNITS')
      WRITE(KO,403) PIGA
  403 FORMAT('      INLET PRESSURE  ',12('. '),'PIGA  ',G12.6,'  ATM')
      WRITE(KO,404) H1M
  404 FORMAT('      INLET HEIGHT  ',13('. '),'H1M   ',G12.6,'  CM')
      WRITE(KO,405) WT1M
  405 FORMAT('      WIDTH IN FLOW DIRECTION ',8('. '),'WT1M  ',G12.6,
     1 '  CM')
      WRITE(KO,406) CL1M
  406 FORMAT('      LENGTH  ',16('. '),'CL1M  ',G12.6,'  CM')
      WRITE(KO,408) DCM
  408 FORMAT('      INLET HYDRAULIC DIAMETER  ',7('. '),'DCM   ',G12.6,
     1 '  CM')
      WRITE(KO,407) PLKW
  407 FORMAT('      LASER OUTPUT POWER  . . ',8('. '),'PLKW  ',G12.6,
     1 '  KW')
      WRITE(KO,401) EFFLP
  401 FORMAT('      LASER EFFICIENCY  ',11('. '),'EFFLP ',G12.6,
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     1  '  PERCENT')
      WRITE(KO,409) NDSGN
  409 FORMAT('     DESIGN OPTION ',13('. '),'NDSGN ',I7,5X,'  -')
      IF (NDSGN .NE. 3) GO TO 50
      WRITE(KO,410) NCS
  410 FORMAT('     NUMBER OF AREAS (NDSGN=3) ',7('. '),'NCS    ',
     1  I7,5X,'  -')
      WRITE(KO,411) (ACN(K),K=1,NCS)
  411 FORMAT('     AREAS ',17('. '),'ACN    ',6(G12.6,1X),
     1  3(51X,6(G12.6,1X)))
      WRITE(KO,412)
  412 FORMAT(65X,'FT**2')
   50 WRITE(KO,413) FN
  413 FORMAT('     GAS MIXTURE ',14('. '),'FN     ',4F6.2,
     1  '  HE  TO  N2  TO  CO2  TO  CO')
      WRITE(KO,414)
  414 FORMAT('0INITIAL ESTIMATE OF STEADY STATE QUANTITIES',
     1  36X,'IF = 0.,USES')
      WRITE(KO,415) ETIG
  415 FORMAT('     GAS STATIC TEMPERATURE - STATION 1',3('. '),'ETIG   ',
     1  G12.6,'  DEG R',10X,'TA1 + 20.')
      WRITE(KO,416) ET02G
  416 FORMAT('     GAS TOTAL TEMPERATURE - STATION 2 ',3('. '),'ET02G ',
     1  G12.6,'  DEG R',10X,'TA1 + 210.')
      WRITE(KO,417) ET06G
  417 FORMAT('     GAS TOTAL TEMPERATURE - STATION 6 ',3('. '),'ET06G ',
     1  G12.6,'  DEG R',10X,'TA1 + 30.')
      WRITE(KO,418) ET07G
  418 FORMAT('     GAS TOTAL TEMPERATURE - STATION 7 ',3('. '),'ET07G ',
     1  G12.6,'  DEG R',10X,'TA1 + 70.')
      WRITE(KO,419) ET1
      WRITE(KO,420) ET2
      WRITE(KO,421) ET3
      WRITE(KO,422) ET4
      WRITE(KO,423) ET6
      WRITE(KO,424) ET8
      WRITE(KO,425) ET10
      WRITE(KO,426) ET14
      WRITE(KO,427) ET16
      WRITE(KO,428) ET18
      WRITE(KO,429) ET20
  419 FORMAT('     COOLANT TEMPERATURE - STATION  1  ',3('. '),'ET1    ',
     1  G12.6,'  DEG R',10X,'TA1 + 20.')
  420 FORMAT('     COOLANT TEMPERATURE - STATION  2  ',3('. '),'ET2    ',
     1  G12.6,'  DEG R',10X,'TA1 + 20.')
  421 FORMAT('     COOLANT TEMPERATURE - STATION  3  ',3('. '),'ET3    ',
     1  G12.6,'  DEG R',10X,'TA1 + 40.')
  422 FORMAT('     COOLANT TEMPERATURE - STATION  4  ',3('. '),'ET4    ',
     1  G12.6,'  DEG R',10X,'TA1 + 55.')
  423 FORMAT('     COOLANT TEMPERATURE - STATION  6  ',3('. '),'ET6    ',
     1  G12.6,'  DEG R',10X,'TA1 + 30.')
  424 FORMAT('     COOLANT TEMPERATURE - STATION  8  ',3('. '),'ET8    ',
     1  G12.6,'  DEG R',10X,'TA1 + 65.')
  425 FORMAT('     COOLANT TEMPERATURE - STATION 10  ',3('. '),'ET10   ',
     1  G12.6,'  DEG R',10X,'TA1 + 65.')
  426 FORMAT('     COOLANT TEMPERATURE - STATION 14  ',3('. '),'ET14   ',
     1  G12.6,'  DEG R',10X,'TA1 + 30.')
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427 FORMAT('      COOLANT TEMPERATURE - STATION 16  ',3('. '),'ET16  ',
   1  G12.6,'  DEG R',10X,'TA1 + 75.')
428 FORMAT('      COOLANT TEMPERATURE - STATION 18  ',3('. '),'ET18  ',
   1  G12.6,'  DEG R',10X,'TA1 + 65.')
429 FORMAT('      COOLANT TEMPERATURE - STATION 20  ',3('. '),'ET20  ',
   1  G12.6,'  DEG R',10X,'TA1 + 65.')
    WRITE(KO,430) ETA2
430 FORMAT('      AIR TEMPERATURE AFTER RADIATOR  ',4('. '),'ETA2  ',
   1  G12.6,'  DEG R',10X,'TA1 + 30.')
    WRITE(KO,431) EBPR
431 FORMAT('      BLOWER PRESSURE RATIO ',9('. '),'EBPR  ',G12.6,
   1        '   -',14X,'1.17')
    WRITE(KO,402) EVIM
402 FORMAT('      INLET VELOCITY  ',12('. '),'EVIM  ',G12.6,'  M/SEC',
   1  10X,'120.')
    WRITE(KO,432)
432 FORMAT('0COOLING SYSTEM FLOWS')
    WRITE(KO,433) WI
433 FORMAT('      HEAT EXCHANGER 1 (LIQUID) ',7('. '),'WI    ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,434) WII
434 FORMAT('      HEAT EXCHANGER 2 (LIQUID) ',7('. '),'WII   ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,435) WB
435 FORMAT('      MIRROR BYPASS ',13('. '),'WB    ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,436) WM
436 FORMAT('      MIRROR  ',16('. '),'WM    ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,437) WV1
437 FORMAT('      VACUUM PUMP 1 ',13('. '),'WV1   ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,438) WV2
438 FORMAT('      VACUUM PUMP 2 ',13('. '),'WV2   ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,439) WE
439 FORMAT('      E-BEAM  ',16('. '),'WE    ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,440) WS
440 FORMAT('      SUSTAINER ',15('. '),'WS    ',
   1  G12.6,'  LB/SEC')
    WRITE(KO,441) CWA
441 FORMAT('      CORRECTED FAN FLOW (AIR)  ',7('. '),'CWA   ',
   1  G12.6,'  CFM')
    WRITE(KO,445)
445 FORMAT('0SPECIFICATIONS OF BLOWERS')
    WRITE(KO,442) ATAP
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442 FORMAT('      BLOWER POLYTROPIC EFFICIENCY  ',5('. '),'ATAB  ',
   1  G12.6,'  -')
    WRITE(KO,446) BRPM
446 FORMAT('      BLOWER SPEED  ',13('. '),'BRPM  ',G12.6,'  RPM')
    WRITE(KO,447) NBS
447 FORMAT('      NUMBER OF BLOWER SETS ',9('. '),'NBS   ',I6,6X,
   1  '  -')
    WRITE(KO,448) NBPS
448 FORMAT('      NUMBER OF BLOWERS PER SET ',7('. '),'NBPS  ',
   1  I6,6X,'  -')
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      WRITE(KO,543) VLIM
  543 FORMAT('      INLET VELOCITY TOLERANCE  ',7('. '),'VLIM  ',
     1  G12.6,'  M/SEC')
      WRITE(KO,444)
  444 FORMAT('0TUNNEL AREAS')
      WRITE(KO,443) A
  443 FORMAT('      STATION 1 TO STATION 11 ',8('. '),'A     ',
     1  6(1X,G12.6   )/50X,5(1X,G12.6   ),'FT**2')
      WRITE(KO,100)
      WRITE(KO,101) TITLE
      WRITE(KO,500)
  500 FORMAT('0     INPUT LIST (CONT.)')
      WRITE(KO,501)
  501 FORMAT('0HEAT EXCHANGER SPECIFICATIONS',23X,'EXCHANGER 1',5X,
     1  'EXCHANGER 2',7X,'RADIATOR',3X,'UNITS')
      WRITE(KO,502)
  502 FORMAT(9X,'DESCRIPTION',25X,'NAME',8X,'(1)',13X,'(2)',14X,'(3)')
      WRITE(KO,503) DL
  503 FORMAT('      CORE LENGTH (GAS) ',11('. '),'DL    ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,504) DH
  504 FORMAT('      CORE HEIGHT ',14('. '),'DH    ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,505) DW
  505 FORMAT('      CORE WIDTH (LIQUID) ',10('. '),'DW    ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,506) DDHG
  506 FORMAT('      HYDRAULIC DIAMETER (GAS)  ',7('. '),'DDHG ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,507) DALG
  507 FORMAT('      SURFACE AREA / VOLUME (GAS) ',6('. '),'DALG ',
     1  3(2X,G12.6,2X),'1/FT')
      WRITE(KO,508) DAFOA
  508 FORMAT('      FIN AREA / SURFACE AREA (GAS) ',5('. '),'DAFOA',
     1  3(2X,G12.6,2X),'-')
      WRITE(KO,509) DSIG
  509 FORMAT('      FREE FLOW AREA / FACE AREA (GAS)  ',3('. '),'DSIG ',
     1  3(2X,G12.6,2X),'-')
      WRITE(KO,510) DDEL
  510 FORMAT('      FIN THICKNESS (GAS) ',10('. '),'DDEL ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,511) DSL
  511 FORMAT('      FIN LENGTH (GAS)  ',11('. '),'DSL  ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,516) DDH
  516 FORMAT('      HYDRAULIC DIAMETER (LIQUID) ',6('. '),'DDH  ',
     1  3(2X,G12.6,2X),'FT')
      WRITE(KO,514) DALF
  514 FORMAT('      SURFACE AREA / VOLUME (LIQUID)  ',4('. '),'DALF ',
     1  3(2X,G12.6,2X),'1/FT')
      WRITE(KO,550) DAFAL
  550 FORMAT('      FIN AREA / SURFACE AREA (LIQUID)  ',3('. '),'DAFAL',
     13(2X,G12.6,2X),'-')
      WRITE(KO,515) DSI
  515 FORMAT('      FREE FLOW AREA / FACE AREA (LIQUID) ',2('. '),
     1  'DSI  ',3(2X,G12.6,2X),'-')
      WRITE(KO,512) DA
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512 FORMAT('      FIN THICKNESS (LIQUID)  ',8('. '),'DA    ',
   1  3(2X,G12.6,2X),'FT')
    WRITE(KO,551) DSLL
551 FORMAT('      FIN LENGTH (LIQUID) ',10('. '),'DSLL ',
   13(2X,G12.6,2X),'FT')
    WRITE(KO,552) AB
552 FORMAT('      PARTING PLATE THICKNESS ',8('. '),'AB    ',
   13(2X,G12.6,2X),'FT')
    WRITE(KO,541) NP
541 FORMAT('      NUMBER OF LIQUID PASSES ',8('. '),'NP    ',
   1  3(5X,I4,7X),'-')
    WRITE(KO,513) DKH
513 FORMAT('      FIN THERMAL CONDUCTIVITY  ',7('. '),'DKH  ',
   1  3(2X,G12.6,2X),'BTU/HR-FT-DEG R')
    WRITE(KO,517)
517 FORMAT('0HEAT INPUT RATES',39X,'VALUE      UNITS')
    WRITE(KO,518) QP
518 FORMAT('      PUMP  ',17('. '),'QP    ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,519) QCM
519 FORMAT('      MIRROR CONTROL  ',12('. '),'QCM  ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,520) QM
520 FORMAT('      MIRROR  ',16('. '),'QM    ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,521) QV1
521 FORMAT('      VACUUM PUMP 1 ',13('. '),'QV1  ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,522) QV2
522 FORMAT('      VACUUM PUMP 2 ',13('. '),'QV2  ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,523) QE
523 FORMAT('      E-BEAM  ',16('. '),'QE    ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,524) QS
524 FORMAT('      SUSTAINER ',15('. '),'QS    ',
   1  2X,G12.6,2X,'BTU/SEC')
    WRITE(KO,525)
525 FORMAT('0DIFFUSER LOSS COEFFICIENTS')
    WRITE(KO,526) CF23
    WRITE(KO,527) CF34
526 FORMAT('      STATION 2  TO  STATION 3  ',7('. '),'CF23 ',
   1  2X,G12.6,2X,'-')
    WRITE(KO,544) CF111
    WRITE(KO,531) CF910
    WRITE(KO,530) CF89
    WRITE(KO,529) CF78
    WRITE(KO,528) CF45
527 FORMAT('      STATION 3  TO  STATION 4  ',7('. '),'CF34 ',
   1  2X,G12.6,2X,'-')
528 FORMAT('      STATION 4  TO  STATION 5  ',7('. '),'CF45 ',
   1  2X,G12.6,2X,'-')
529 FORMAT('      STATION 7  TO  STATION 8  ',7('. '),'CF78 ',
   1  2X,G12.6,2X,'-')
530 FORMAT('      STATION 8  TO  STATION 9  ',7('. '),'CF89 ',
   1  2X,G12.6,2X,'-')
531 FORMAT('      STATION 9  TO  STATION 10 ',7('. '),'CF910',
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     1  2X,G12.6,2X,'-')
 544 FORMAT('      STATION 11 TO  STATION 1  ',7('. '),'CF111',
     1  2X,G12.6,2X,'-')
      WRITE(KO,532)
 532 FORMAT('0AMBIENT CONDITIONS, DECISION VARIABLES, AND CONVERGENCE',
     1  ' TOLERANCES')
      WRITE(KO,533)  TA1F
 533 FORMAT('      AMBIENT TEMPERATURE ',10('. '),'TA1F ',2X,G12.6,2X,
     1  'DEG F')
      WRITE(KO,534) PAT
 534 FORMAT('      AMBIENT PRESSURE  ',11('. '),'PAT  ',2X,G12.6,2X,
     1  'PSIA')
      WRITE(KO,535) RHP
 535 FORMAT('      RELATIVE HUMIDITY ',11('. '),'RHP  ',2X,G12.6,2X,
     1  'PERCENT')
      WRITE(KO,542) FG
 542 FORMAT('      FRACTION OF GLYCOL IN COOLING LIQUID  . FG     ',
     1  G12.6, '  -')
      WRITE(KO,536) NLIM
 536 FORMAT('      MAXIMUM NUMBER OF LOOP CYCLES ',5('. '),'NLIM ',
     1  5X,I3,8X,'-')
      WRITE(KO,537) PLIM
 537 FORMAT('      PRESSURE TOLERANCE  ',10('. '),'PLIM ',2X,G12.6,2X,
     1  'PSIA')
      WRITE(KO,538) DELM
 538 FORMAT('      MACH NUMBER TOLERANCE ',9('. '),'DELM ',2X,G12.6,2X,
     1  '-')
      WRITE(KO,539) ROLIM
 539 FORMAT('      DENSITY TOLERANCE ',11('. '),'ROLIM',2X,G12.6,2X,
     1  'LB/FT**3')
      WRITE(KO,540) CONV
 540 FORMAT('      STATE VARIABLE TOLERANCES ',7('. '),'CONV ',
     1  5(2X,G12.6,1X),2(/50X,5(2X,G12.6,1X))/50X,2X,G12.6,2X,
     2  'DEG R')
      WRITE(KO,100)
 100 FORMAT('1')
      WRITE(KO,101) TITLE
 101 FORMAT(21X,14A6)
      CALL GASP(TIG, FN, GAMIG, Z, Z, Z, GMU)
      CALL GASP(T2G, FN, GAM2G, Z, Z, Z, GMU)
      CALL GASP(T3G, FN, GAM3G, Z, Z, Z, GMU)
      CALL GASP(T4G, FN, GAM4G, Z, Z, Z, GMU)
      CALL GASP(T5G, FN, GAM5G, Z, Z, Z, GMU)
      CALL GASP(T6G, FN, GAM6G, Z, Z, Z, GMU)
      CALL GASP(T7G, FN, GAM7G, Z, Z, Z, GMU)
      CALL GASP(T8G, FN ,GAM8G, Z, Z, Z, GMU)
      CALL GASP(T9G, FN ,GAM9G, Z, Z, Z, GMU)
      CALL GASP(T10G, FN, GAM10G, Z, Z, Z, GMU)
      CALL GASP(T11G, FN, GAM11G, Z, Z, Z, GMU)
      CON=32.174*1545.43/GMU
      VG(1)=FM1*DSQRT(GAMIG*CON*TIG)
      VG(2)=FM2*DSQRT(GAM2G*CON*T2G)
      VG(3)=FM3*DSQRT(GAM3G*CON*T3G)
      VG(4)=FM4*DSQRT(GAM4G*CON*T4G)
      VG(5)=FM5*DSQRT(GAM5G*CON*T5G)
      VG(6)=FM6*DSQRT(GAM6G*CON*T6G)
      VG(7)=FM7*DSQRT(GAM7G*CON*T7G)
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      VG(8)=FM8*DSQRT(GAM8G*CON*T8G)
      VG(9)=FM9*DSQRT(GAM9G*CON*T9G)
      VG(10)=FM10*DSQRT(GAM10G*CON*T10G)
      VG(11)=FM11*DSQRT(GAM11G*CON*T11G)
      DO 28 K=1,11
   28 QG(K)=VG(K)*A(K)*60.
      WRITE(KO,102) ALT
  102 FORMAT('0  ALTITUDE  ',20('. '),1X,G12.6,' (K FT)')
      WRITE(KO,103) PAT
  103 FORMAT('    AMBIENT PRESSURE  ',16('. '),1X,G12.6,' (PSIA)')
      WRITE(KO,104) TA1F
  104 FORMAT('    AMBIENT TEMPERATURE ',15('. '),1X,G12.6,' (DEG F)')
      WRITE(KO,105) RHP
  105 FORMAT('    RELATIVE HUMIDITY ',16('. '),1X,G12.6,' (PERCENT)')
      WRITE(KO,107) PIGA
  107 FORMAT('    LASER INLET PRESSURE  ',14('. '),1X,G12.6,' (ATM)')
      TIGM=TIG/1.8
      WRITE(KO,108)
  108 FORMAT('    LASER INLET TEMPERATURE ',13('. '),1X,G12.6,' (DEG K)')
      Z=(T02G-T01G)/1.8
      WRITE(KO,142) Z
  142 FORMAT('    TEMPERATURE RISE ACROSS CAVITY  ',9('. '),1X,G12.6,
     1  ' (DEG K)')
      WRITE(KO,109) VIM
  109 FORMAT('    LASER INLET VELOCITY  ',14('. '),1X,G12.6,' (M/SEC)')
      WRITE(KO,110) PLKW
  110 FORMAT( '    LASER OUTPUT POWER . . ',13('. '),1X,G12.6,' (KW)')
      WRITE(KO,141) EFFLP
  141 FORMAT( '    LASER EFFICIENCY  ',16('. '),1X,G12.6,' (PERCENT)')
      WRITE(KO,114) WG
  114 FORMAT('    LASER GAS MASS FLOW RATE  ',12('. '),1X,G12.6,
     1  ' (LB/SEC)')
      WRITE(KO,115) Q6G
  115 FORMAT( '    VOLUME FLOW RATE AT BLOWER INLET  ',8('. '),1X,G12.6,
     1  ' (CFM)')
      WRITE(KO,116) QCORR
  116 FORMAT( '    CORRECTED VOLUME FLOW RATE AT BLOWER INLET  ',3('. '),
     1  1X,G12.6,' (CFM)')
      WRITE(KO,139) WA
  139 FORMAT( '    COOLING AIR FLOW RATE ',14('. '),1X,G12.6,
     1  ' (LB/SEC)')
      WRITE(KO,140) CWA
  140 FORMAT( '    COOLING AIR FLOW RATE ',14('. '),1X,G12.6,
     1  '(CFM)')
      WRITE(KO,117) BPR
  117 FORMAT( '    BLOWER PRESSURE RATIO ',14('. '),1X,G12.6,' (-)')
      WRITE(KO,111) BLPRM, BLPR
  111 FORMAT( '    BLOWER POWER REQUIRED ',14('. '),1X,G12.6,' (KW)',
     1  8X,G12.6,1X,' (HP)')
      WRITE(KO,112) PPRM, PPR
  112 FORMAT( '    COOLING PUMP POWER REQUIRED ',11('. '),1X,G12.6,
     1  ' (KW)',8X,G12.6,1X,' (HP)')
      WRITE(KO,113) PFM, PF
  113 FORMAT('    COOLING FAN POWER REQUIRED  ',11('. '),1X,G12.6,
     1  ' (KW)',8X,G12.6,1X,' (HP)')
      WRITE(KO,106) FN
  106 FORMAT('    LASER GAS MIXTURE ',16('. '),1X,F5.2,3(' TO',F5.2),2X,
```

```
     1  '(HE TO N2 TO CO2 TO CO)')
        WRITE(KO,143) GMU
  143   FORMAT('   MOLECULAR WEIGHT OF GAS   ',12('. '),1X,G12.6,
     1  ' (-)')
        WRITE(KO,118)
  118   FORMAT('0',8X,'HEAT EXCHANGER VARIABLES',15X,'EXCHANGER 1',6X,
     1  'EXCHANGER 2',7X,'RADIATOR',8X,'UNITS')
        WRITE(KO,119) QDI, QDII, QDA
  119   FORMAT('   HEAT TRANSFER RATE  ',11('. '),2X,3(G12.6,5X),
     1  ' BTU/HR')
        WRITE(KO,120) DPI, DPII, DP
  120   FORMAT('   LIQUID PRESSURE DROP  ',10('. '),2X,3(G12.6,5X),
     1  ' PSIA')
        WRITE(KO,121) NP
  121   FORMAT('   NUMBER OF LIQUID PASSES ',9('. '),2X,3(6X,I2,9X),' -')
        NFULL=0
        IF (NFULL .NE. 0)  RETURN
        WRITE(KO,122) TMI, TMII, TM
  122   FORMAT('   MEAN TEMPERATURE ',9('.') ,'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' DEG R')
        WRITE(KO,123) TGMI, TGMII, TMA
  123   FORMAT(32X,'(GAS)',10X,3(G12.6,5X))
        WRITE(KO,124) ZIMU, ZIIMU, ZMU
  124   FORMAT('   VISCOSITY ',16('.'),'(LIQUID)',4('. '),2X,3(G12.6,5X),
     1  ' LB/FT-SEC')
        WRITE(KO,123) GIMU, GIIMU, AMU
        WRITE(KO,125) PRI, PRII, PR
  125   FORMAT('   PRANDTL NUMBER ',11('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' -')
        WRITE(KO,123) PRGI, PRGII, PRA
        WRITE(KO,126) CPI, CPII, CP
  126   FORMAT('   SPECIFIC HEAT ',12('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' BTU/LB-DEG R')
        WRITE(KO,123) CPGI, CPGII, CPA
        WRITE(KO,127) GI, GII, G
  127   FORMAT('   MASS FLUX ',16('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' LB/FT**2-SEC')
        WRITE(KO,123) GGI, GGII, GA
        WRITE(KO,128) REI, REII, RE
  128   FORMAT('   REYNOLDS NUMBER ',10('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' -')
        WRITE(KO,123) REGI, REGII, REA
        WRITE(KO,129) FI, FII, F
  129   FORMAT('   FRICTION FACTOR ',10('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' -')
        WRITE(KO,123) GFI, GFII, AF
        WRITE(KO,130) ZJI, ZJII, ZJ
  130   FORMAT('   HEAT TRANSFER FACTOR ',5('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' -')
        WRITE(KO,123) GJI, GJII, AJ
        WRITE(KO,131) HI, HII, H
  131   FORMAT('   HEAT TRANSFER COEF. ',6('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' BTU/FT**2-SEC-DEG R')
        WRITE(KO,123) HGI, HGII, HA
        WRITE(KO,132) CI, CII, C
  132   FORMAT('   FLUID CAPACITY RATE ',6('.'),'(LIQUID)',4('. '),2X,
     1  3(G12.6,5X),' BTU/SEC-DEG R')
```

```
      WRITE(KO,123) CGI, CGII, CA
      WRITE(KO,133) UI, UII, U
  133 FORMAT('   OVERALL HEAT TRANSFER COEF. ',7('. '),2X,3(G12.6,5X),
     1 ' BTU/FT**2-SEC-DEG R')
      WRITE(KO,134) AGI, AGII, AA
  134 FORMAT('   GAS HEAT TRANSFER SURFACE AREA  ',5('. '),2X,
     1  3(G12.6,5X),' FT**2')
      WRITE(KO,135) TUNI, TUNII, TUN
  135 FORMAT('   NUMBER OF TRANSFER UNITS  ',8('. '),2X,
     1  3(G12.6,5X),' -')
      WRITE(KO,136) TOWI, TOWII, TOW
  136 FORMAT('   CAP GAMMA ',16('. '),2X,3(G12.6,5X),' -')
      WRITE(KO,137) ESSI, ESSII, ESS
  137 FORMAT('   SINGLE PASS EFFECTIVENESS ',8('. '),2X,
     1  3(G12.6,5X),' -')
      WRITE(KO,138) EPSI, EPSII, EPSA
  138 FORMAT('   TOTAL EFFECTIVENESS ',11('. '),2X,
     1  3(G12.6,5X),' -')
      WRITE(KO,100)
      WRITE(KO,101) TITLE
      WRITE(KO,200)
  200 FORMAT('0',16X,'GAS FLOW SYSTEM VARIABLES BY STATION')
      WRITE(KO,201)
  201 FORMAT('0    STATION NUMBER',18X,'1',13X,'2',13X,'3',13X,'4',
     1  13X,'5',13X,'6'/37X,'7',13X,'8',13X,'9',12X,'10',12X,'11')
      WRITE(KO,204) P01G, P02G, P03G, P04G, P05G, P06G, P07G, P08G,
     1  P09G, P010G, P011G
  204 FORMAT('0    TOTAL PRESSURE       (PSIA)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,203) PIG, P2G, P3G, P4G, P5G, P6G, P7G, P8G, P9G, P10G,
     1  P11G
  203 FORMAT('0    STATIC PRESSURE      (PSIA)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,206) T01G, T02G, T03G, T04G, T05G, T06G, T07G, T08G,
     1  T09G, T010G, T011G
  206 FORMAT('0    TOTAL TEMP.          (DEG R)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,205) TIG, T2G, T3G, T4G, T5G, T6G, T7G, T8G, T9G, T10G,
     1  T11G
  205 FORMAT('0    STATIC TEMPERATURE (DEG R)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,207) FM1, FM2, FM3, FM4, FM5, FM6, FM7, FM8, FM9, FM10,
     1  FM11
  207 FORMAT('0    MACH NUMBER               (-)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,208) VG
  208 FORMAT('0    VELOCITY             (FT/SEC)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,209) QG
  209 FORMAT('0    VOL. FLOW RATE         (CFM)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      Z=GMU*.093178
      ROG( 1)=PIG*Z/TIG
      ROG( 2)=P2G*Z/T2G
      ROG( 3)=P3G*Z/T3G
      ROG( 4)=P4G*Z/T4G
      ROG( 5)=P5G*Z/T5G
```

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      ROG( 6)=P6G*Z/T6G
      ROG( 7)=P7G*Z/T7G
      ROG( 8)=P8G*Z/T8G
      ROG( 9)=P9G*Z/T9G
      ROG(10)=P10G*Z/T10G
      ROG(11)=P11G*Z/T11G
      WRITE(KO,220) ROG
220   FORMAT('0    DENSITY          (LB/FT**3)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,212) A
212   FORMAT('0     AREA                   (FT**2)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      WRITE(KO,213) GAM1G, GAM2G, GAM3G, GAM4G, GAM5G, GAM6G, GAM7G,
     1  GAM8G, GAM9G, GAM10G, GAM11G
213   FORMAT('0     GAMMA                  (-)',
     1  6(1X,G12.6,1X)/31X,5(1X,G12.6,1X))
      PD(1) = (P01G-P02G)*27.7
      PD(2)=(P02G-P03G)*27.7
      PD(3)=(P03G-P04G)*27.7
      PD(4)=(P04G-P05G)*27.7
      PD(5)=(P05G-P06G)*27.7
      PD(6)=(P06G-P07G)*27.7
      PD(7)=(P07G-P08G)*27.7
      PD(8)=(P08G-P09G)*27.7
      PD(9)=(P09G-P010G)*27.7
      PD(10)=(P010G-P011G)*27.7
      PD(11)=(P011G-P01G)*27.7
      DO 27 K=1,11
27    PP(K)=PD(K)/(27.7*P06G)
      WRITE(KO,210) PD
210   FORMAT('0     PRESSURE DROP     (IN H2O)',6X,
     1  6(1X,G12.6,1X)/37X,5(1X,G12.6,1X))
      WRITE(KO,211) PP
211   FORMAT('0     PRESSURE DROP / P06     (-)',6X,
     1  6(1X,G12.6,1X)/37X,5(1X,G12.6,1X))
      WRITE(KO,214)
214   FORMAT('0',12X,'COOLING AIR VARIABLES')
      WRITE(KO,215)
215   FORMAT('0     STATION NUMBER',18X,'1A',12X,'2A')
      WRITE(KO,216) PA1, PA2
216   FORMAT('0     PRESSURE',12X,'(PSIA)',2(1X,G12.6,1X))
      WRITE(KO,217) TA1, TA2
217   FORMAT('0     TEMPERATURE',8X,'(DEG R)',2(1X,G12.6,1X))
      WRITE(KO,218) ROA1, ROA2
218   FORMAT('0     DENSITY',9X,'(LB/FT**3)',2(1X,G12.6,1X))
      DPPA=(PA1-PA2)*27.7
      WRITE(KO,219) DPPA
219   FORMAT('0     PRESSURE DROP      (IN H2O)',7X,G12.6)
      WRITE(KO,100)
      WRITE(KO,101) TITLE
      WRITE(KO,300)
300   FORMAT('0',16X,'COOLING SYSTEM VARIABLES BY STATION')
      WRITE(KO,301)
301   FORMAT('0     STATION NUMBER',19X,'1',13X,'2',13X,'3',13X,'4',13X,
     1  '5',13X,'6',13X,'7'/38X,'8',13X,'9',12X,'10',12X,'11',12X,
     2  '12',12X,'13',12X,'14',/37X,'15',12X,'16',12X,'17',12X,'18',
     3  12X,'19',12X,'20')
```

```
      WRITE(KO,302) P
  302 FORMAT('0     PRESSURE               (PSIA)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,303) T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12,
     1  T13, T14, T15, T16, T17, T18, T19, T20
  303 FORMAT('0     TEMPERATURE            (DEG R)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,304) VC
  304 FORMAT('0     VELOCITY             (FT/SEC)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,305) QC
  305 FORMAT('0     VOL. FLOW RATE (FT**3/SEC)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,306) QCG
  306 FORMAT('0     VOL. FLOW RATE   (GAL/MIN)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,307) DPC
      WRITE(KO,309) AC
  309 FORMAT('0     AREA                   (FT**2)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
  307 FORMAT('0     PRESSURE DROP          (PSIA)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      WRITE(KO,308) DPCR
  308 FORMAT('0     PRESSURE DROP / P1       (-)',
     1  7(1X,G12.6,1X)/31X,7(1X,G12.6,1X)/31X,6(1X,G12.6,1X))
      RETURN
      END
```

```
$FPT
NTAM    =          +0
TA1F    =      -.120000000000000000D+003
PLKW    =       .500000000000000000D+002
ETIG    =       .000000000000000000D+000
ET02G   =       .000000000000000000D+000
ET06G   =       .000000000000000000D+000
ET07G   =       .000000000000000000D+000
ET1     =       .000000000000000000D+000
ET2     =       .000000000000000000D+000
ET3     =       .000000000000000000D+000
ET4     =       .000000000000000000D+000
ET6     =       .000000000000000000D+000
ETA2    =       .000000000000000000D+000
ET14    =       .000000000000000000D+000
ET16    =       .000000000000000000D+000
ET8     =       .000000000000000000D+000
ET10    =       .000000000000000000D+000
ET18    =       .000000000000000000D+000
ET20    =       .000000000000000000D+000
EFFLP   =       .100000000000000000D+002
WI      =       .100000000000000000D+001
WII     =       .917399999999999999D+000
WB      =       .500000000000000000D+000
WM      =       .908000000000000000D+000
WV1     =       .909999999999999999D-001
WV2     =       .818000000000000000D+000
WE      =       .908000000000000000D+000
WS      =       .454999999999999999D+001
CWA     =       .500000000000000000D+005
QP      =       .350000000000000000D+001
QCM     =       .950000000000000000D+000
QM      =       .472999999999999999D+001
QV1     =       .473000000000000000D+000
QV2     =       .425999999999999999D+001
QE      =       .472999999999999999D+001
QS      =       .237000000000000000D+002
CF23    =       .799999999999999999D-001
CF34    =       .150000000000000000D+000
CF45    =       .300000000000000000D-001
CF78    =       .150000000000000000D+000
CF89    =       .150000000000000000D+000
CF910   =       .300000000000000000D-001
CF111   =       .150000000000000000D+000
EVIM    =       .250000000000000000D+002
ATAP    =       .700000000000000000D+000
PIGA    =       .100000000000000000D+001
H1M     =       .500000000000000000D+001
CL1M    =       .400000000000000000D+002
WT1M    =       .500000000000000000D+001
FN      =       .300000000000000000D+001,       .200000000000000000D+001,
                .500000000000000000D+000,       .500000000000000000D+000
ACN     =       .000000000000000000D+000,       .000000000000000000D+000,
                .000000000000000000D+000,       .000000000000000000D+000,
                .000000000000000000D+000,       .000000000000000000D+000,
                .000000000000000000D+000,       .000000000000000000D+000,
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                   .00000000000000000D+000,     .00000000000000000D+000,
                   .00000000000000000D+000,     .00000000000000000D+000,
                   .00000000000000000D+000,     .00000000000000000D+000,
                   .00000000000000000D+000,     .00000000000000000D+000,
                   .00000000000000000D+000,     .00000000000000000D+000,
                   .00000000000000000D+000,     .00000000000000000D+000
DCM       =        .86259999999999999D+001
DL        =        .20000000000000000D+001,     .20000000000000000D+001,
                   .22812500000000000D+001
DH        =        .66666699999999999D+000,     .66666699999999999D+000,
                   .19792917000000000D+002
DW        =        .20000000000000000D+001,     .20000000000000000D+001,
                   .60416699999999999D+000
DDHG      =        .25500000000000000D-002,     .20200000000000000D-002,
                   .78199999999999998D-002
DALG      =        .24460600000000000D+003,     .24460600000000000D+003,
                   .33675999999999999D+003
DAFOA     =        .86300000000000000D+000,     .86300000000000000D+000,
                   .80899999999999999D+000
DSIG      =        .76989738999999999D+000,     .76989738999999999D+000,
                   .65836579999999999D+000
DDEL      =        .49999999999999999D-003,     .49999999999999999D-003,
                   .49999999999999999D-003
DA        =        .49999999999999999D-003,     .49999999999999999D-003,
                   .49999999999999999D-003
DKH       =        .10000000000000000D+003,     .10000000000000000D+003,
                   .10000000000000000D+003
DSL       =        .22650000000000000D-001,     .22650000000000000D-001,
                   .10458300000000000D-001
DSI       =        .72717999999999999D-001,     .72717999999999999D-001,
                   .13328000000000000D+000
DALF      =        .72717999999999999D+002,     .72717999999999999D+002,
                   .13328000000000000D+003
DDH       =        .99999999999999997D-003,     .99999999999999997D-003,
                   .39999999999999999D-002
NP        =              +1,            +1,           +4
PAT       =        .14690000000000000D+002
RHP       =        .10000000000000000D+003
FBPR      =        .00000000000000000D+000
A         =        .21529217000066052D+000,     .00000000000000000D+000,
                   .54539999999999999D+000,     .54539999999999999D+000,
                   .54539999999999999D+000,     .34910000000000000D+000,
                   .54539999999999999D+000,     .54539999999999999D+000,
                   .54539999999999999D+000,     .54539999999999999D+000,
                   .43055641600000000D+000
CONV      =        .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000,
                   .50000000000000000D+000,     .50000000000000000D+000
DELM      =        .99999999999999997D-003
NDSGN     =              +2
NCS       =              +1
NLIM      =              +20
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ROLIM    =            .10000000000000000D-004
PLIM     =            .99999999999999997D-003
FG       =            .00000000000000000D+000
BRPM     =            .11200000000000000D+005
VLIM     =            .50000000000000000D+000
NBS      =                  +7
NBPS     =                  +2
JCPRO    =                  -1
RO1      =            .41500000000000000D-002
DAFAL    =            .50799999999999999D+000,            .50799999999999999D+000,
                      .50799999999999999D+000
DSLL     =            .21166700000000000D-002,            .21166700000000000D-002,
                      .21166700000000000D-002
AB       =            .20833000000000000D-002,            .20833000000000000D-002,
                      .20833000000000000D-002
```

Table 1

```
                    LASER TEST CASE
                    DECEMBER 1976

      INPUT LIST
  CAVITY * LASER SPECIFICATIONS
          DESCRIPTION                             NAME     VALUE         UNITS
      INLET PRESSURE . . . . . . . . . . . . . . PIGA    .100000+001    ATM
      INLET HEIGHT . . . . . . . . . . . . . . . H1M     .500000+001    CM
      WIDTH IN FLOW DIRECTION . . . . . . . . . WT1M    .500000+001    CM
      LENGTH . . . . . . . . . . . . . . . . . . CL1M    .400000+002    CM
      INLET HYDRAULIC DIAMETER . . . . . . . . . DCM     .862600+001    CM
      LASER OUTPUT POWER . . . . . . . . . . . . PLKW    .500000+002    KW
      LASER EFFICIENCY . . . . . . . . . . . . . EFFLP   .100000+002    PERCENT
      DESIGN OPTION . . . . . . . . . . . . . . NDSGN        2          -
      GAS MIXTURE . . . . . . . . . . . . . . . FN        3.00  2.00     .50
                                                .50   HE   TO  N2   TO   CO2  TO  CO
  INITIAL ESTIMATE OF STEADY STATE QUANTITIES                                IF = 0.,USES
      GAS STATIC TEMPERATURE - STATION 1. . . . ETIG    .000000         DEG R  TA1 + 20.
      GAS TOTAL TEMPERATURE - STATION 2 . . . . ET02G   .000000         DEG R  TA1 + 210.
      GAS TOTAL TEMPERATURE - STATION 6 . . . . ET06G   .000000         DEG R  TA1 + 30.
      GAS TOTAL TEMPERATURE - STATION 7 . . . . ET07G   .000000         DEG R  TA1 + 70.
      COOLANT TEMPERATURE - STATION  1  . . . . ET1     .000000         DEG R  TA1 + 20.
      COOLANT TEMPERATURE - STATION  2  . . . . ET2     .000000         DEG R  TA1 + 20.
      COOLANT TEMPERATURE - STATION  3  . . . . ET3     .000000         DEG R  TA1 + 40.
      COOLANT TEMPERATURE - STATION  4  . . . . ET4     .000000         DEG R  TA1 + 55.
      COOLANT TEMPERATURE - STATION  6  . . . . ET6     .000000         DEG R  TA1 + 30.
      COOLANT TEMPERATURE - STATION  8  . . . . ET8     .000000         DEG R  TA1 + 65.
      COOLANT TEMPERATURE - STATION 10  . . . . ET10    .000000         DEG R  TA1 + 65.
      COOLANT TEMPERATURE - STATION 14  . . . . ET14    .000000         DEG R  TA1 + 30.
      COOLANT TEMPERATURE - STATION 16  . . . . ET16    .000000         DEG R  TA1 + 75.
      COOLANT TEMPERATURE - STATION 18  . . . . ET18    .000000         DEG R  TA1 + 65.
      COOLANT TEMPERATURE - STATION 20  . . . . ET20    .000000         DEG R  TA1 + 65.
      AIR TEMPERATURE AFTER RADIATOR  . . . . . ETA2    .000000         DEG R  TA1 + 30.
      BLOWER PRESSURE RATIO . . . . . . . . . . EBPR    .000000         -      1.17
      INLET VELOCITY . . . . . . . . . . . . . . EVIM    .250000+002    M/SEC 120.

  COOLING SYSTEM FLOWS
      HEAT EXCHANGER 1 (LIQUID) . . . . . . . . WI      .100000+001    LB/SEC
      HEAT EXCHANGER 2 (LIQUID) . . . . . . . . WII     .917400+000    LB/SEC
      MIRROR BYPASS . . . . . . . . . . . . . . WB      .500000+000    LB/SEC
      MIRROR . . . . . . . . . . . . . . . . . . WM      .908000+000    LB/SEC
      VACUUM PUMP 1 . . . . . . . . . . . . . . WV1     .910000-001    LB/SEC
      VACUUM PUMP 2 . . . . . . . . . . . . . . WV2     .818000+000    LB/SEC
      E-BEAM . . . . . . . . . . . . . . . . . . WE      .908000+000    LB/SEC
      SUSTAINER . . . . . . . . . . . . . . . . WS      .455000+001    LB/SEC
      CORRECTED FAN FLOW (AIR) . . . . . . . . . CWA     .500000+005    CFM

  SPECIFICATIONS OF BLOWERS
      BLOWER POLYTROPIC EFFICIENCY . . . . . . ATAB    .700000+000    -
      BLOWER SPEED . . . . . . . . . . . . . . . ERPM    .112000+005    RPM
      NUMBER OF BLOWER SETS . . . . . . . . . . NBS        7           -
      NUMBER OF BLOWERS PER SET . . . . . . . . NBPS       2           -
      INLET VELOCITY TOLERANCE . . . . . . . . . VLIM    .500000+000    M/SEC

  TUNNEL AREAS
      STATION 1 TO STATION 11 . . . . . . . . . A       .215299+000   .215299+000

                   .545400+000  .545400+000  .545400+000  .349100+000

      .545400+000  .545400+000  .545400+000  .545400+000  .430556+000FT**2
```

LASER TEST CASE
DECEMBER 1976

INPUT LIST (CONT.)

HEAT EXCHANGER SPECIFICATIONS

DESCRIPTION	NAME	EXCHANGER 1 (1)	EXCHANGER 2 (2)	RADIATOR (3)	UNITS
CORE LENGTH (GAS)	DL	.200000+001	.200000+001	.228125+001	FT
CORE HEIGHT	DH	.666667+000	.666667+000	.197929+002	FT
CORE WIDTH (LIQUID)	DW	.200000+001	.200000+001	.604167+000	FT
HYDRAULIC DIAMETER (GAS)	DDHG	.255000-002	.202000-002	.782000-002	FT
SURFACE AREA / VOLUME (GAS)	DALG	.244606+003	.244606+003	.336760+003	1/FT
FIN AREA / SURFACE AREA (GAS)	DAFOA	.863000+000	.863000+000	.809000+000	-
FREE FLOW AREA / FACE AREA (GAS) . . .	DSIG	.769897+000	.769897+000	.658366+000	-
FIN THICKNESS (GAS)	DDEL	.500000-003	.500000-003	.500000-003	FT
FIN LENGTH (GAS)	DSL	.226500-001	.226500-001	.104583-001	FT
HYDRAULIC DIAMETER (LIQUID)	DDH	.100000-002	.100000-002	.400000-002	FT
SURFACE AREA / VOLUME (LIQUID)	DALF	.727180+002	.727180+002	.133280+003	1/FT
FIN AREA / SURFACE AREA (LIQUID) . . .	DAFAL	.508000+000	.508000+000	.506000+000	-
FREE FLOW AREA / FACE AREA (LIQUID) . .	DSI	.727180-001	.727180-001	.133280+000	-
FIN THICKNESS (LIQUID)	DA	.500000-003	.500000-003	.500000-003	FT
FIN LENGTH (LIQUID)	DSLL	.211667-002	.211667-002	.211667-002	FT
PARTING PLATE THICKNESS	AB	.208330-002	.208330-002	.208330-002	FT
NUMBER OF LIQUID PASSES	NP	1	1	4	-
FIN THERMAL CONDUCTIVITY	DKH	.100000+003	.100000+003	.100000+003	BTU/HR-FT-DEG R

HEAT INPUT RATES

		VALUE	UNITS
PUMP	GP	.350000+001	BTU/SEC
MIRROR CONTROL	GCM	.950000+000	BTU/SEC
MIRROR	GM	.473000+001	BTU/SEC
VACUUM PUMP 1	GV1	.473000+000	BTU/SEC
VACUUM PUMP 2	GV2	.426000+001	BTU/SEC
E-BEAM	GE	.473000+001	BTU/SEC
SUSTAINER	GS	.237000+002	BTU/SEC

```
DIFFUSER LOSS COEFFICIENTS
    STATION 2  TO  STATION 3  . . . . . . . . CF23     .800000-001  -
    STATION 3  TO  STATION 4  . . . . . . . . CF34     .150000+000  -
    STATION 11 TO  STATION 1  . . . . . . . . CF111    .150000+000  -
    STATION 9  TO  STATION 10 . . . . . . . . CF910    .300000-001  -
    STATION 8  TO  STATION 9  . . . . . . . . CF89     .150000+000  -
    STATION 7  TO  STATION 8  . . . . . . . . CF78     .150000+000  -
    STATION 4  TO  STATION 5  . . . . . . . . CF45     .300000-001  -

AMBIENT CONDITIONS, DECISION VARIABLES, AND CONVERGENCE TOLERANCES
    AMBIENT TEMPERATURE . . . . . . . . . . . TA1F    -.120000+003  DEG F
    AMBIENT PRESSURE  . . . . . . . . . . . . PAT      .146900+002  PSIA
    RELATIVE HUMIDITY . . . . . . . . . . . . RHP      .100000+003  PERCENT
    FRACTION OF GLYCOL IN COOLING LIQUID  . . FG       .000000      -
    MAXIMUM NUMBER OF LOOP CYCLES . . . . . . NLIM        20        -
    PRESSURE TOLERANCE  . . . . . . . . . . . PLIM     .100000-002  PSIA
    MACH NUMBER TOLERANCE . . . . . . . . . . DELM     .100000-002  -
    DENSITY TOLERANCE . . . . . . . . . . . . ROLIM    .100000-004  LB/FT**3
    STATE VARIABLE TOLERANCES . . . . . . . . CONV     .500000+000
                                                       .500000+000
                                                       .500000+000
                                          .500000+000  .500000+000  .500000+000  .500000+000
                                          .500000+000  .500000+000  .500000+000  .500000+000
                                          .500000+000  .500000+000  .500000+000  .500000+000

                                               .500000+000  DEG R
```

Table 2

LASER TEST CASE
DECEMBER 1976

ALTITUDE	.000000 (K FT)	
AMBIENT PRESSURE	.146900+002 (PSIA)	
AMBIENT TEMPERATURE	-.120000+003 (DEG F)	
RELATIVE HUMIDITY	.100000+003 (PERCENT)	
LASER INLET PRESSURE	.100000+001 (ATM)	
LASER INLET TEMPERATURE		
TEMPERATURE RISE ACROSS CAVITY	.518021+003 (DEG K)	
LASER INLET VELOCITY	.250000+002 (M/SEC)	
LASER OUTPUT POWER	.500000+002 (KW)	
LASER EFFICIENCY	.100000+002 (PERCENT)	
LASER GAS MASS FLOW RATE	.119226+001 (LB/SEC)	
VOLUME FLOW RATE AT BLOWER INLET	.134604+004 (CFM)	
CORRECTED VOLUME FLOW RATE AT BLOWER INLET . . .	.108659+004 (CFM)	
COOLING AIR FLOW RATE	.787055+002 (LB/SEC)	
COOLING AIR FLOW RATE	.500000+005(CFM)	
BLOWER PRESSURE RATIO	.102468+001 (-)	
BLOWER POWER REQUIRED	.255385+001 (KW)	.342476+001 (HP)
COOLING PUMP POWER REQUIRED	.000000 (KW)	.000000 (HP)
COOLING FAN POWER REQUIRED	.171500+002 (KW)	.229985+002 (HP)
LASER GAS MIXTURE	3.00 TO 2.00 TO .50 TO	.50 (HE TO N2 TO CO2 TO CO)
MOLECULAR WEIGHT OF GAS	.173403+002 (-)	

HEAT EXCHANGER VARIABLES	EXCHANGER 1	EXCHANGER 2	RADIATOR	UNITS
HEAT TRANSFER RATE	.131815+007	.129876+006	.160046+007	BTU/HR
LIQUID PRESSURE DROP	.000000	.000000	.000000	PSIA
NUMBER OF LIQUID PASSES	1	1	4	-
MEAN TEMPERATURE ....(LIQUID). . . .	.523942+003	.361018+003	.363978+003	DEG R
(GAS)	.787989+003	.389408+003	.356417+003	
VISCOSITY ....(LIQUID). . . .	.100000-004	.100000-004	.100000-004	LB/FT-SEC
(GAS)	.168675-004	.990843-005	.923730-005	
PRANDTL NUMBER ....(LIQUID). . . .	.104806+000	.127362+000	.126861+000	-
(GAS)	.479389+000	.425348+000	.734821+000	
SPECIFIC HEAT ....(LIQUID). . . .	.100181+001	.992757+000	.992921+000	BTU/LB-DEG R
(GAS)	.360665+000	.348516+000	.2[illegible]9295+000	

MASS FLUX ....(LIQUID). . . .	.103138+002	.946189+001	.243254+002	LB/FT**2-SEC
(GAS)	.116155+001	.116155+001	.264762+001	
REYNOLDS NUMBER ....(LIQUID). . . .	.103138+004	.946186+003	.973012+004	-
(GAS)	.175601+003	.236801+003	.224139+004	
FRICTION FACTOR ....(LIQUID). . . .	.000000	.000000	.000000	-
(GAS)	.829930-001	.764029-001	.405812-001	
HEAT TRANSFER FACTOR .....(LIQUID). . . .	.102923-001	.106279-001	.520734-002	-
(GAS)	.241728-001	.189830-001	.106194-001	
HEAT TRANSFER COEF. ......(LIQUID). . . .	.478400+000	.394376+000	.498162+000	BTU/FT**2-SEC-DEG R
(GAS)	.165327-001	.135872-001	.826233-002	
FLUID CAPACITY RATE ......(LIQUID). . . .	.100181+001	.910755+000	.962379+001	BTU/SEC-DEG R
(GAS)	.430044+000	.415558+000	.188338+002	
OVERALL HEAT TRANSFER COEF.	.114758-001	.994101-002	.762488-002	BTU/FT**2-SEC-DEG R
GAS HEAT TRANSFER SURFACE AREA	.652283+003	.652283+003	.918671+004	FT**2
NUMBER OF TRANSFER UNITS	.174063+002	.156040+002	.7 859+001	-
CAP GAMMA	.999431+000	.999191+000	.6 371+000	-
SINGLE PASS EFFECTIVENESS	.902531+000	.888069+000	.6 167+000	-
TOTAL EFFECTIVENESS	.902531+000	.888069+000	.9 673+000	-

LASER TEST CASE
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GAS FLOW SYSTEM VARIABLES BY STATION

STATION NUMBER		1 7	2 8	3 9	4 10	5 11	6
TOTAL PRESSURE	(PSIA)	.147491+002	.147336+002	.147191+002	.147148+0	.147140+002	.145106+002
		.148668+002	.148673+002	.148659+002	.148656+0	.147509+002	
STATIC PRESSURE	(PSIA)	.147000+002	.145526+002	.146907+002	.146869+0	.146861+002	.144874+002
		.148590+002	.148576+002	.148561+002	.148559+0	.147383+002	
TOTAL TEMP.	(DEG R)	.352197+003	.128463+004	.128499+004	.128499+0	.128499+004	.433205+003
		.439012+003	.438851+003	.438851+003	.438851+0	.352164+003	
STATIC TEMPERATURE	(DEG R)	.351809+003	.128017+004	.128423+004	.128425+0	.128425+004	.432819+003
		.438754+003	.438754+003	.438754+003	.438754+0	.352068+003	
MACH NUMBER	(-)	.668419-001	.131289+000	.514212-001	.514390-0	.514420-001	.464788-001
		.292112-001	.292139-001	.292167-001	.292172-0	.333528-001	
VELOCITY	(FT/SEC)	.820249+002	.301524+003	.118273+003	.118315+0	.118322+003	.631488+002
		.399536+002	.399573+002	.399611+002	.399619+0	.409436+002	
VOL. FLOW RATE	(CFM)	.105959+004	.389507+004	.387038+004	.387174+0	.387196+004	.132271+004
		.130744+004	.130756+004	.130769+004	.130771+0	.105771+004	
DENSITY	(LB/FT**3)	.675120-001	.183673-001	.184829-001	.184780-0	.184769-001	.540822-001
		.547191-001	.547139-001	.547087-001	.547076-0	.676383-001	
AREA	(FT**2)	.215299+000	.215299+000	.545400+000	.545400+0	.545400+000	.349100+000
		.545400+000	.545400+000	.545400+000	.545400+0	.430556+000	
GAMMA	(-)	.149276+001	.143688+001	.143664+001	.143664+0	.143664+001	.148737+001
		.148695+001	.148695+001	.148695+001	.148695+0	.149274+001	
PRESSURE DROP	(IN H2O)	.429226+000	.401079+000	.117872+000	.23[illegible]65-001	.563475+001	-.992112+001
		.391339-001	.391719-001	.783509-002	.31[illegible]07+001	.507868-001	
PRESSURE DROP / P06	(-)	.106788-002	.997850-003	.293255-003	.57[illegible]08-004	.140188-001	-.246829-001
		.973618-004	.974562-004	.194930-004	.79[illegible]76-002	.126353-003	

APPENDIX B
(David Washington)

Phase Diagram for a Mixture of (a) Carbon Dioxide and (b) Nitrogen, at (P = 1 atm) Pressure

<u>Condition for Phase Equilibrium</u>

$$\bar{f}_A^{\,1} = \bar{f}_A^{\,2}$$

or, at equilibrium the fugacity of a given component is the same in each phase. In general,

$$\bar{f}_A^1 = \bar{f}_A^2 = \bar{f}_A^3 = \ . \ . \ . \text{ for all phases}$$

$$\bar{f}_B^1 = \bar{f}_B^2 = \bar{f}_B^3 = \ . \ . \ . \text{ for all phases}$$

- - -

- - -

for all components.

Pure Carbon Dioxode at 1 atm pressure will exist as a vapor or solid, depending on the temperature (See P-T diagram). Pure Nitrogen at 1 atm pressure can exist in all three phases (vapor, liquid, solid), depending on temperature (See P-T diagram). However, the fugacity of compressed liquids and solids can be treated alike, as follows.

For a pure substance at constant temperature,

$$R\,T\,(d \ln f)_T = v\,d\,P_T$$

integrating between saturation state on Pressure P,

$$R\,T \int_{f^{SAT}}^{f} d\,(\ln f)_T = \int_{P^{SAT}}^{P} v\ d\,P_T$$

Assume constant specific volume (v) for liquids and solids.

$$R\,T\ \ln \frac{f}{f^{SAT}} \approx v\,(P - P^{SAT})$$

$$\frac{f}{f^{SAT}} \approx e^{\frac{v\,(P-P^{SAT})}{RT}}$$

Since v is small for liquids and solids, the quantity $v\,(P - P^{SAT})$ is small for moderate changes of pressure. Therefore,

$$\frac{f}{f^{SAT}} \underset{\substack{\text{liquid}\\ \text{and}\\ \text{solids}}}{\approx} e^{0} = 1$$

or

$$f^{L} \approx f^{SAT} \qquad , \qquad f^{S} \approx f^{SAT}$$

For Nitrogen at,

$$T = 200^{o}R$$

$$P^{SAT} = 226.853\ \frac{Lbf}{in^2}$$

$$v = .02613\ ft^3/Lbm$$

$$R + 55.15\ \frac{ft\text{-}Lbf}{Lbm^{o}R}$$

$$P = 1\ atm$$

$$\frac{f}{f^{SAT}} \approx e^{-.072} = .93$$

Therefore, $f \approx f^{SAT}$ with 7% error at this check point.

From the P-T chart for Nitrogen, it is observed that only a small portion of the liquid phase is involved (since 1 atm is near the triple point). Also, since the fugacity of liquids and solids are calculated alike ($f^L = f^S \approx f^{SAT}$) it is felt that the Nitrogen component can be considered in two phases (solid and vapor) for this problem. Consequently, for this problem (1 atm), consider a Binary Solution (vapor and solid) of two components (A- Carbon Dioxide, and B-Nitrogen). Therefore,

$$\bar{f}_{N_2}^{\,2} = \bar{f}_{N_2}^{\,V}$$

Condition for Equilibrium

$$\bar{f}_{CO_2}^{\,S} = \bar{f}_{CO_2}^{\,V}$$

<u>Additional Assumptions</u>

1) Assume Ideal Solution.

$$\bar{f}_i^{\,\phi} = y_i^{\phi} \; f_i^{\phi}$$

where

ϕ = phase

i = component

$\bar{f}_i^{\phi}$ = fugacity of component (i) in phase (ϕ)

f_i^{ϕ} = fugacity of Pure (i) in the same phase as the mixture on the same temperature and pressure

y_i^{ϕ} = mole fraction of (i)

or

$$Z_A \, f_A^S = y_A \, f_A^V$$

$$Z_B \, f_B^S = y_B \, f_B^V$$

where,

$$Z_A = \text{mole fraction of (A) in Solid Phase}$$

$$Z_B = \text{mole fraction of (B) in Solid Phase}$$

$$y_A = \text{mole fraction of (A) in Vapor Phase}$$

$$y_B = \text{mole fraction of (B) in Vapor Phase}$$

2) Assume,

$$f_A^S = f_A^{SAT}$$

$$f_B^S = f_B^{SAT}$$

As discussed earlier

3) Assume that pure saturated vapor at T and P^{SAT} behave as an ideal gas. Therefore,

$$f_A^{SAT} = P_A^{SAT} \text{ (Vapor Pressure)}_A$$

$$f_B^{SAT} = P_B^{SAT} \text{ (Vapor Pressure)}_B$$

4) For the Vapor Phase, assume that pure gas (A) and pure gas (B) behave as ideal gases at T and P. Therefore,

$$f_A^V = P$$

$$f_B^V = P$$

Combining (1), (2), (3), and (4),

$$Z_A \; P_A^{SAT} = y_A \; P$$

$$Z_B \; P_B^{SAT} = y_B \; P$$

Known as (RAOULT'S LAW). Good for systems at Low Pressure.

Combined with, $\begin{bmatrix} Z_A + Z_B = 1 \\ y_A + y_B = 1 \end{bmatrix}$

gives a system of four equations and four unknowns (Z_A, Z_B, y_A, y_B).

Combining final equations,

$$(1) \quad Z_A \; P_A^{SAT} = y_A \, P$$

$$(2) \quad Z_B \; P_B^{SAT} = y_B \, P$$

$$(3) \quad Z_A + Z_B = 1$$

$$(4) \quad y_A + y_B = 1$$

$$Z_A \frac{P_A^{SAT}}{P} + Z_B \frac{P_B^{SAT}}{P} = 1$$

$$Z_A \frac{P_A^{SAT}}{P_B^{SAT}} + (1 - Z_A) = \frac{P}{P_B^{SAT}}$$

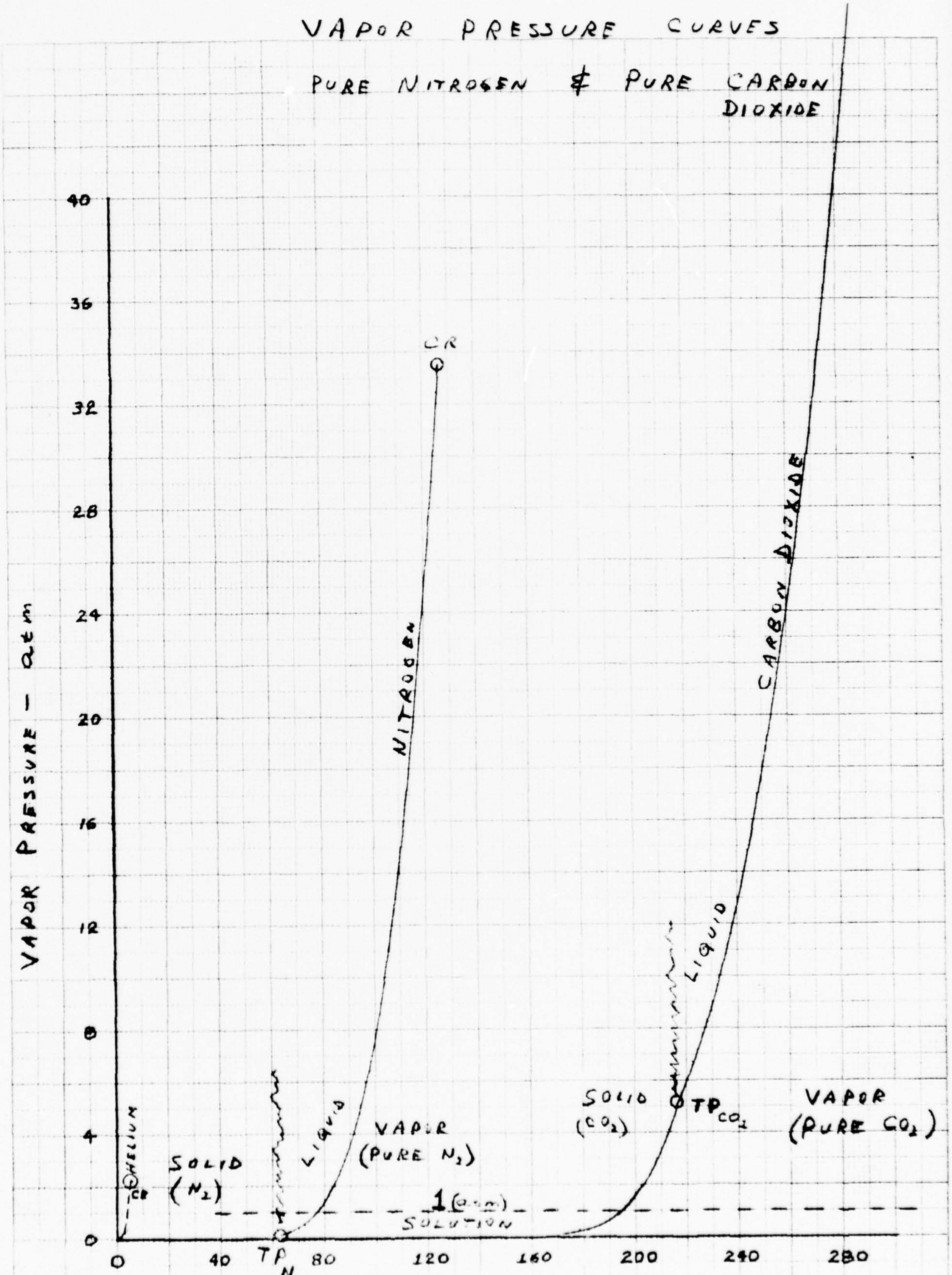
$$Z_A \left[\frac{P_A^{SAT}}{P_B^{SAT}} - 1 \right] = \frac{P}{P_B^{SAT}} - 1$$

$$Z_A = \frac{P - P_B^{SAT}}{P_A^{SAT} - P_B^{SAT}}$$

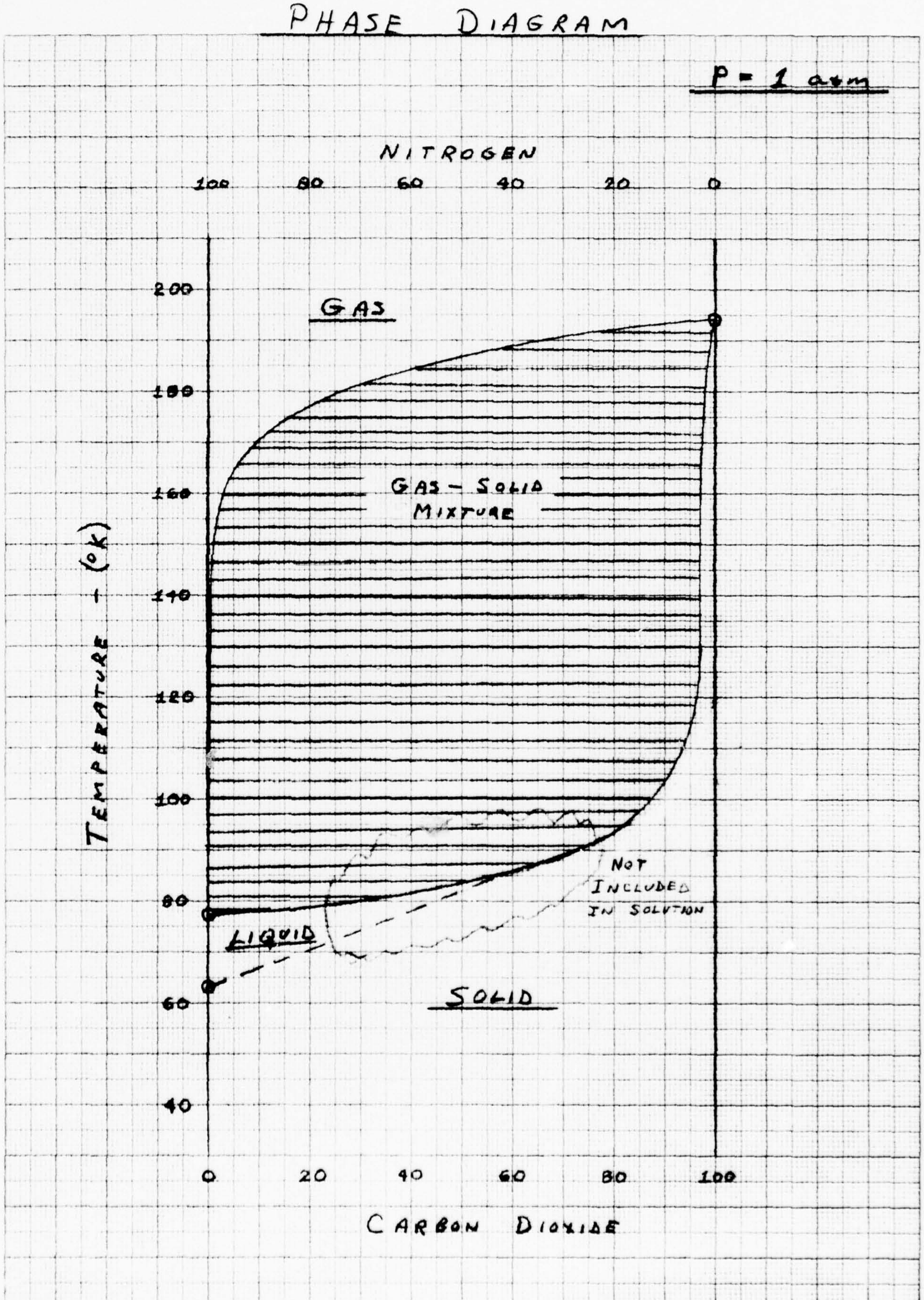
$$y_A = Z_A \frac{P_A^{SAT}}{P}$$

CRITICAL POINT AND TRIPLE POINT PROPERTIES
OF PURE NITROGEN AND CARBON DIOXIDE

		(B) NITROGEN (N_2)	(A) CARBON DIOXIDE (CO_2)
MOLECULAR WEIGHT		28.013 $\frac{\text{Lb mass}}{\text{Lb mole}}$	44.01 $\frac{\text{Lb mass}}{\text{Lb mole}}$
	Z_C	.291	.275
CRITICAL POINT	T_C	126.2°K	304.2°K
	T_C	227.1°R	547.5°R
	T_C	-232.57°F	87.8°F
	P_C	33.5 atm	72.9 atm
	P_C	492. Lbf/in^2	1071. Lbf/in^2
TRIPLE POINT	T_{TP}	63.15°K (-210°C)	216.55°K (-56.6°C)
	T_{TP}	113.67°R	389.79°R
	T_{TP}	-345.6°F	-69.88°F
	P_{TP}	94.01 mmhg	3885.1 mmhg
	P_{TP}	.1237 atm	5.112 atm
	P_{TP}	1.818 Lbf/in^2	75.126 Lbf/in^2
SATURATION DATA AT P = 1 atm	T_{SAT}	139.255°R (L-V)	350.3°R
		-320.415°F (-195.786C)	-109.3°F (-78.52°C)
		77.364°K	194.63°K



VAPOR PRESSURE CURVES
PURE NITROGEN & PURE CARBON DIOXIDE
VAPOR PRESSURE - atm
TEMPERATURE - °K
0
4
8
12
16
20
24
28
32
36
40
0
40
80
120
160
200
240
280
CR
NITROGEN
CARBON DIOXIDE
LIQUID
LIQUID
HELIUM
CR
SOLID
(N_2)
VAPOR
(PURE N_2)
SOLID
(CO_2)
VAPOR
(PURE CO_2)
TP_{CO_2}
TP
N_2
1 (atm)
SOLUTION


PHASE DIAGRAM
P = 1 atm
NITROGEN
100
80
60
40
20
0
200
180
160
140
120
100
80
60
40
TEMPERATURE - (°K)
GAS
GAS - SOLID MIXTURE
NOT INCLUDED IN SOLUTION
LIQUID
SOLID
0
20
40
60
80
100
CARBON DIOXIDE

Phase Diagram for a Mixture of (A) Nitrogen and (B) Helium, at (P = 1 atm) Pressure

Solution

Assume a binary solution (solid-vapor) at two components. Assume an ideal solution and using Raoult's Law, as in Appendix A, we have,

$$\begin{aligned} &\text{(solid)} && \text{(vapor)} \\ &Z_A\, P_A^{SAT} &=\ & y_A\, P \\ &Z_B\, P_B^{SAT} &=\ & y_B\, P \end{aligned} \qquad \text{RAOULT'S LAW}$$

Combine with,

$$Z_A + Z_B = 1$$

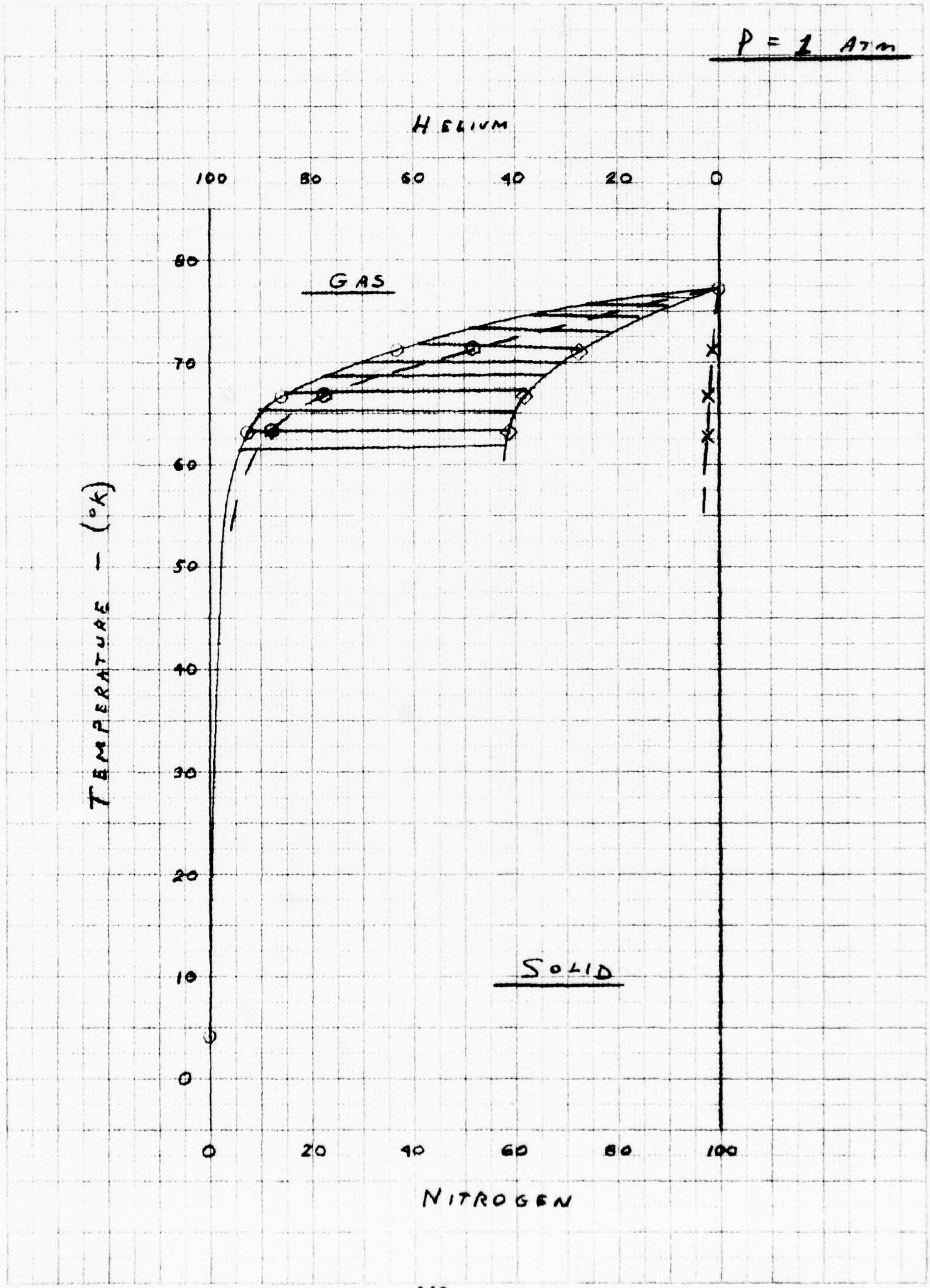
$$y_A + y_B = 1$$

yield

$$Z_A = \frac{P - P_B^{SAT}}{P_A^{SAT} - P_B^{SAT}}$$

$$y_A = Z_A \frac{P_A^{SAT}}{P}$$

PHASE DIAGRAM



Phase Diagram for a Mixture of (A) Carbon Dioxide and (B) Helium at (P = 1 atm) Pressure

<u>Solution</u>

Assume a binary solution (solid-vapor) of two components. Assume an ideal solution and using Raoult's Law, as in Appendix A and B, we have,

$$\begin{array}{ccc} \text{(solid)} & & \text{(vapor)} \\ Z_A P_A^{SAT} & = & y_A P \\ Z_B P_B^{SAT} & = & y_B P \end{array} \qquad \text{RAOULT'S LAW}$$

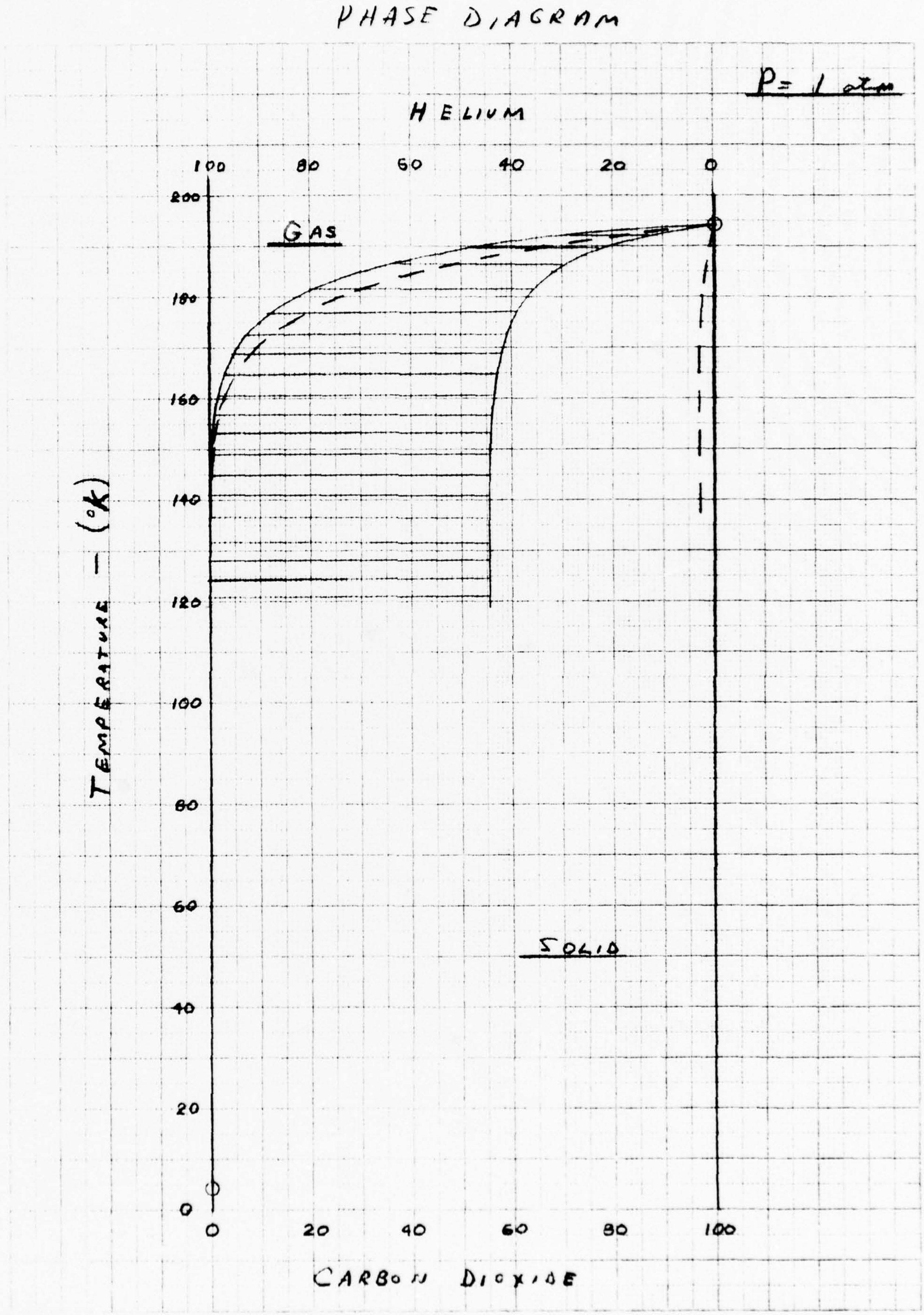
Combine with,

$$Z_A + Z_B = 1$$

$$y_A + y_B = 1$$

$$Z_A = \frac{P - P_B^{SAT}}{P_A^{SAT} - P_B^{SAT}}$$

$$y_A = Z_A \frac{P_A^{SAT}}{P}$$


PHASE DIAGRAM
P= 1 atm
HELIUM
100
80
60
40
20
0
200
180
160
140
120
100
80
60
40
20
0
GAS
SOLID
TEMPERATURE — (°K)
0
20
40
60
80
100
CARBON DIOXIDE

APPENDIX C

```
      PARAMETER M=12, JJ=41, ISEG=100, II=ISEG+1, N=18
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL

      DIMENSION X1(M),X2(M),X3(M),P(M,II,JJ),BC1(M),BC2(M),BIC(M)
      DIMENSION SW(N),SL(N),SR(N),WL(N),WR(N)
      PARAMETER NZ=4
      DIMENSION CSL(NZ),CSR(NZ)
      COMMON /DLL/ CSL,CSR,SL,SR
      DO 50 L=1,2
C DEFINE CONSTANTS
      IF(L.EQ.1) XNN=1.0
      IF(L.EQ.2) XNN=-1.0
      SEG=ISEG
      IC=II-1
      MI=II-2
      MJ=JJ-1
      BC11=0.0
      BC21=200.0
      X=BC21-BC11
      DX=X/SEG
      DIS=6.0
      CP=0.24
      G=1.4
      RF=53.34
      XP=2116.8
      XD=0.00234
      XU=100.0
      AZ=0.0
      ZERO=0.0
      HX=4.0
      F=0.02
      XL=1.0
      CV=CP/G
      RR=RF/778.161
      R=RF*32.1739
      XT=XP/XD/R
      A=SQRT(G*R*XT)
      U=XU/A
      CA=(G-1.0)/(2.0*G)
      CB=(G+1.0)/(2.0*G)
      CC=2.0/(G+1.0)
C BOUNDARY CONDITIONS (LEFT)
      BC1(1)=BC11
      BC1(2)=-10.0
      BC1(3)=U
      BC1(4)=1.0
      BC1(5)=0.0
      BC1(6)=0.0
      BC1(7)=0.25
      BC1(8)=XP
      BC1(9)=XD
      BC1(10)=XT
      BC1(11)=0.2
C BOUNDARY CONDITIONS (RIGHT)
      BC2(1)=BC21
      BC2(2)=-10.0
      BC2(3)=U
      BC2(4)=1.0
      BC2(5)=0.0
```

```
      BC2(6 )=0.0
      BC2(7 )=0.25
      BC2(8 )=XP
      BC2(9 )=XD
      BC2(10)=XT
      BC2(11)=0.2
C FLOW DIRECTIONS
      BC1(3 )=BC1(3)*XNN
      BC2(3 )=BC2(3)*XNN
C LOAD BOUNDARY CONDITIONS
      DO 15 J=1,MJ
      DO 14 K=1,M
      P(K,1 ,J)=BC1(K)
      P(K,II,J)=BC2(K)
   14 CONTINUE
   15 CONTINUE
C INITIAL CONDITIONS
      DO 18 I=2,IC
      IM1 = I-1
      P(1,I ,1)=P(1,IM1,1)+DX
   18 CONTINUE
      BIC(2 )=0.0
      BIC(3 )=U
      BIC(4 )=1.0
      BIC(5 )=0.0
      BIC(6 )=0.0
      BIC(7 )=0.25
      BIC(8 )=XP
      BIC(9 )=XD
      BIC(10)=XT
      BIC(11)=0.2
C FLOW DIRECTIONS
      BIC(3 )=BIC(3)*XNN
C LOAD INITIAL CONDITIONS
      DO 17 I=2,IC
      DO 16 K=2,M
      P(K,I ,1)=BIC(K)
   16 CONTINUE
   17 CONTINUE
C SHOCK WAVE
      SW(1) =100.0
      SW(2) = 0.0
      SW(3) =1.13
      PRES= 1.323
      DENS= 1.221
      TEMP= 1.084
      SPEED =SQRT(TEMP)
      D1=BIC(9)
      S1=BIC(5)
      T1=BIC(10)
      QQ=(200.0)*(9.478E-4)*(28.32)
      Q=(QQ /D1)*(1.0/32.1739)
      DS=Q/ T1
      T2=Q/ CV+T1
      P2=D1 *R*T2
      A2=SQRT(G*R*T2)/A
```

```
      S2=DS/G/RR+S1
      SW(4)=CC*(SW(3)-1.0/SW(3))+BIC(3)
      SW(5)=BIC(3)
      SW(6)=PRES*BIC(8)
      SW(7)=BIC(8)
      SW(8)=DENS*BIC(9)
      SW(9)=BIC(9)
      SW(10)=TEMP*BIC(10)
      SW(11)=BIC(10)
      SW(12)=SPEED*BIC(4)
      SW(13)=BIC(4)
      SH=CP*ALOG(TEMP)-RR*ALOG(PRES)
      SW(14)=SH/G/RR+BIC(5)
      SW(15)=BIC(5)
      SW(16)=BIC(6)
      SW(17)=BIC(7)
      SW(18)=BIC(11)
      SL(1)=SW(1)-DIS
      SR(1)=SW(1)+DIS
      DO 32 IK=2,N
      SL(IK)=SW(IK)
      SR(IK)=SW(IK)
 32   CONTINUE
      SL(3)=-SW(3)
      SL(4)=SW(5)+(2.0/(G+1.0))*(SL(3)-1.0/SL(3))
C   CONTACT SURFACE
      YA=PRES-1.0
      YB=2.C/G
      YC=(G+1.0)*PRES
      YD=G-1.0
      YF=YA*SQRT(YB/(YC+YD))
      YF=0.C
      CSL(1)=SL(1)
      CSL(2)=SL(2)
      CSL(3)=U-YF
      CSL(4)=-1.0
      CSR(1)=SR(1)
      CSR(2)=SR(2)
      CSR(3)=U+YF
      CSR(4)=+1.0
      WRITE(6,300)
 300  FORMAT(8X,'LOCATION',8X,'TIME',8X,'MACH',10X,'U2',10X,'U1',10X,
     1       'P2',10X,'P1',9X,'RO2',9X,'RO1')
      WRITE(6,301)
 301  FORMAT(14X,'T2',10X,'T1',10X,'A2',10X,'A1',10X,'S2',10X,'S1',
     1       7X,'DS/DT',4X,'DIAMETER',4X,'FRICTION')
      WRITE(6,109) (SW(I),I=1,18)
      WRITE(6,109) SL
      WRITE(6,109) SR
 109  FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'MAIN')/)
      DO 33 IK=1,II
      HL=SW(1)-DIS
      HR=SW(1)+DIS
      HHX=P(1,IK,1)
      KK=0
      IF(HHX.GT.HL.AND.HHX.LT.HR) KK=1
```

```
      IF(HHX.EQ.ML.OR.HHX.EQ.MR) KK=-1
      IF(KK) 35,33,34
 34   P(4,IK,1)=A2
      P(5,IK,1)=S2
      P(8,IK,1)=P2
      P(10,IK,1)=T2
      GO TO 33
 35   P(4,IK,1)=SPEED*BIC(4)
      BH=CP*ALOG(TEMP)-RR*ALOG(PRES)
      P(5,IK,1)=BH/G/RR+BIC(5)
      P(8,IK,1)=PRES*BIC(8)
      P(9,IK,1)=DENS*BIC(9)
      P(10,IK,1)=TEMP*BIC(10)
 33   CONTINUE
      U=XNN*U
C SOLUTION
      IS=ISEG/2
      IW=IS+1
      DO 13 J=1,MJ
      DO 12  IZ=1,MI
      I=IW-IZ
      IF(IZ.GE.IW) I=IZ
      DO 10 K=1,M
      X1(K)=P(K,I,J)
      IP2 = I+2
      X2(K)=P(K,IP2,J)
   10 CONTINUE
      DO 30 LI=1,N
      WL(LI)=SL(LI)
      WR(LI)=SR(LI)
 30   CONTINUE
      CALL FIG(M,X1,X2,X3,WL,WR)
      DO 31 LI=1,N
      SL(LI)=WL(LI)
      SR(LI)=WR(LI)
 31   CONTINUE
      DO 11 K=1,M
      IP1 = I+1
      JP1 = J+1
      P(K,I,J)=X1(K)
      P(K,IP2,J)=X2(K)
      P(K,IP1,JP1) = X3(K)
   11 CONTINUE
   12 CONTINUE
   13 CONTINUE
C END SOLUTION
C PRINTOUT
      WRITE(6,1)
    1 FORMAT(1H1,6X,'ARRAY P(K,I,J)')
      WRITE(6,200) XNN
  200 FORMAT(2X,'XNN=',F10.3)
      DO 20 J=1,JJ,10
      DO 19 I=1,II
      WRITE(6,2)(I,J,(P(K,I,J),K=1,M))
 2    FORMAT(2X,I3,2X,I3,12(2X,E8.3))
   19 CONTINUE

      END
```

```
      SUBROUTINE RAN(NN,BB1,BB2,PR,XX)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      DIMENSION BB1(NN),BB2(NN)
      XA=1.0+((G+1.0)/(G-1.0))*PR
      XB=(G-1.0)/(G-1.0)+PR
      BB2(1)=BB1(1)
      BB2(2)=BB1(2)
      BB2(6)=BB1(6)
      BB2(7)=BB1(7)
      BB2(8)=PR*BB1(8)
      BB2(9)=BB1(9)*(XA/XB)
      BB2(10)=BB1(10)*PR*(XB/XA)
      BB2(11)=BB1(11)
      V1=SQRT(CA+CB*PR)
      V2=V1*(BB1(9)/BB2(9))
      BB2(3)=U+XX*(V1-V2)
      BB2(4)=SQRT(G*R*BB2(10))/A
      BH=CP*ALOG(BB2(10)/BB1(10))-RR*ALOG(PR)
      BB2(5)=BH/G/RR+BB1(5)
      RETURN
      END


      SUBROUTINE SUB(N,A,B,C)
      COMMON /DLL/ CSL,CSR,SL,SR
      DIMENSION A(N),B(N),C(N)
      NM=0
      CALL CCS(N,A,B,C,CSL,NM)
      IF(NM) 109,109,107
  109 CONTINUE
      MM=0
      CALL CCS(N,A,B,C,CSR,MM)
      IF(MM) 110,110,107
  110 CONTINUE
      CALL SSS(N,A,B,C)
  107 CONTINUE
      END


      SUBROUTINE COM(NN,C1,C2,C3)
      DIMENSION C1(NN),C2(NN),C3(NN)
      P=(C2(1)-C1(1))/(C3(1)-C1(1))
      DO 10 I=3,NN
      C2(I)=P*C3(I)+(1.0-P)*C1(I)
   10 CONTINUE
      RETURN
      END


      SUBROUTINE PPP(NN,AA1,AA3)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      DIMENSION AA1(NN),AA3(NN)
      C1=(2.0/(G-1.0))*((AA3(4)-AA1(4))/((AA3(4)+AA1(4))/2.0))
      C2=(AA3(5)-AA1(5))*G
      AA3(9)=AA1(9)*(C1-C2+1.0)
      AA3(10)=A*A*AA3(4)*AA3(4)/G/R
      AA3(8)=AA3(9)*R*AA3(10)
      RETURN
      END
```

```
      SUBROUTINE CHKL(NN,AA1,AA2,AA3,AA4,SW,ID)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      PARAMETER  M=12,  N=18
      DIMENSION B2(M),B3(M),C1(M),C3(M),D1(M),D2(M)
      DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN),SW(N)
      DIMENSION E2(M),E3(M),G1(M),F2(M)
      ID=0
      IDR=0
      IDL=0
      IDD=0
      XN=1.0
      SK=(AA2(2)-AA1(2))/(AA2(1)-AA1(1))
      BK=AA1(2)-SK*AA1(1)
      CALL GEO(NN,AA1,AA2,AA3,AA4)
      CALL SIML(NN,AA3,AA2,SW,C3,IDR)
      IF(IDR) 101,101,100
100   RA=AA2(3)+AA2(4)
      SA=1.C/RA
      BA=C3(2)-SA*C3(1)
      C1(1)=(BA-BK)/(SK-SA)
      C1(2)=SK*C1(1)+BK
      CALL COM(NN,AA1,C1,AA2)
      CALL SUB(NN,C1,AA2,C3)
      SW(5)=C3(3)
      SW(7)=C3(8)
      SW(9)=C3(9)
      SW(11)=C3(10)
      SW(13)=C3(4)
      SW(15)=C3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,109) (SW(I),I=1,18)
109   FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'109L')/)
      PR=SW(6)/SW(7)
      CALL RAN(NN,C3,D2,PR,XN)
      CALL SIML(NN,AA1,AA3,SW,B3,IDL)
      IF(IDL) 104,104,103
103   RB=AA1(3)-AA1(4)
      SB=1.C/RB
      BB=B3(2)-SB*B3(1)
      B2(1)=(BB-BK)/(SK-SB)
      B2(2)=SK*C1(1)+BK
      CALL COM(NN,AA1,B2,AA2)
      CALL SUB(NN,AA1,B2,B3)
      SW(5)=B3(3)
      SW(7)=B3(8)
      SW(9)=B3(9)
      SW(11)=B3(10)
      SW(13)=B3(4)
      SW(15)=B3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,110) (SW(I),I=1,18)
110   FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'110L')/)
      PR=SW(6)/SW(7)
      CALL RAN(NN,B3,D1,PR,XN)
      GO TO 104
101   CALL SIML(NN,AA1,AA3,SW,E3,IDD)
      IF(IDD) 104,104,99
99    F2(1)=SW(1)
      F2(2)=SW(2)
      F2(3)=SW(5)
      F2(4)=SW(13)
```

```
      F2(5)=SW(15)
      F2(6)=SW(16)
      F2(7)=SW(17)
      F2(8)=SW(7)
      F2(9)=SW(9)
      F2(10)=SW(11)
      F2(11)=SW(18)
      F2(12)=-1.0
      RC=AA1(3)-AA1(4)
      SC=1.C/RC
      BC=E3(2)-SC*E3(1)
      SS=(F2(2)-AA1(2))/(F2(1)-AA1(1))
      BS=AA1(2)-SS*AA1(1)
      E2(1)=(BS-BC)/(SC-SS)
      E2(2)=SS*E2(1)+BS
      CALL COM(NN,AA1,E2,F2)
      CALL SUB(NN,AA1,E2,E3)
      SW(5)=E3(3)
      SW(7)=E3(8)
      SW(9)=E3(9)
      SW(11)=E3(10)
      SW(13)=E3(4)
      SW(15)=E3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,111)(SW(I),I=1,18)
  111 FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'111L')/)
      PR=SW(6)/SW(7)
      CALL FAN(NN,E3,G1,PR,XN)
  104 IF(IDR .LE. 0 .AND. IDD .LE. 0) GO TO 105
      IF(IDR .GT. 0 .AND. IDL .LE. 0) GO TO 106
      IF(IDR .GT.0 .AND. IDL .GT. 0) GO TO 107
      IF(IDR .LE. 0 .AND. IDD .GT. 0) GO TO 108
  106 CALL SUB(NN,AA1,D2,AA3)
      ID=106
      GO TO 105
  107 CALL SUB(NN,D1,D2,AA3)
      ID=107
      GO TO 105
  108 CALL SUB(NN,G1,AA2,AA3)
      ID=108
  105 RETURN
      END


      SUBROUTINE CHKR(NN,AA1,AA2,AA3,AA4,SW,ID)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      PARAMETER M=12, N=18
      DIMENSION B2(M),B3(M),C1(M),C3(M),D1(M),D2(M)
      DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN),SW(N)
      DIMENSION E1(M),E3(M),G2(M),F1(M)
      ID=0
      IDL=0
      IDR=0
      IDD=0
```

```
      XN=1.0
      SK=(AA2(2)-AA1(2))/(AA2(1)-AA1(1))
      BK=AA1(2)-SK*AA1(1)
      CALL GEO(NN,AA1,AA2,AA3,AA4)
      CALL SIMR(NN,AA1,AA3,SW,B3,IDL)
      IF(IDL) 101,101,100
100   RA=AA1(3)-AA1(4)
      SA=1.0/RA
      BA=B3(2)-SA*B3(1)
      B2(1)=(BA-BK)/(SK-SA)
      B2(2)=SK*B2(1)+BK
      CALL COM(NN,AA1,B2,AA2)
      CALL SUB(NN,AA1,B2,B3)
      SW(5)=B3(3)
      SW(7)=B3(8)
      SW(9)=B3(9)
      SW(11)=B3(10)
      SW(13)=B3(4)
      SW(15)=B3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,109) (SW(I),I=1,18)
109   FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'109R')/)
      PR=SW(6)/SW(7)
      CALL FAN(NN,B3,D1,PR,XN)
      CALL SIMR(NN,AA3,AA2,SW,C3,IDR)
      IF(IDR) 104,104,103
103   RB=AA2(3)+AA2(4)
      SB=1.0/RB
      BB=C3(2)-SB*C3(1)
      C1(1)=(BB-BK)/(SK-SB)
      C1(2)=SK*C1(1)+BK
      CALL COM(NN,AA1,C1,AA2)
      CALL SUB(NN,C1,AA2,C3)
      SW(5)=C3(3)
      SW(7)=C3(8)
      SW(9)=C3(9)
      SW(11)=C3(10)
      SW(13)=C3(4)
      SW(15)=C3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,110) (SW(I),I=1,18)
110   FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'110R')/)
      PR=SW(6)/SW(7)
      CALL FAN(NN,C3,D2,PR,XN)
      GO TO 104
101   CALL SIMR(NN,AA3,AA2,SW,E3,IDD)
      IF(IDD) 104,104,99
 99   F1(1)=SW(1)
      F1(2)=SW(2)
      F1(3)=SW(5)
      F1(4)=SW(13)
      F1(5)=SW(15)
      F1(6)=SW(16)
      F1(7)=SW(17)
```

```
      F1(8)=SW(7)
      F1(9)=SW(9)
      F1(10)=SW(11)
      F1(11)=SW(18)
      F1(12)=-1.0
      RC=AA2(3)+AA2(4)
      SC=1.0/RC
      BC=E3(2)-SC*E3(1)
      SS=(F1(2)-AA2(2))/(F1(1)-AA2(1))
      BB=AA2(2)-SS*AA2(1)
      E1(1)=(BB-BC)/(SC-SS)
      E1(2)=SS*E1(1)+BB
      CALL COM(NN,F1,E1,AA2)
      CALL SUB(NN,E1,AA2,E3)
      SW(5)=E3(3)
      SW(7)=E3(8)
      SW(9)=E3(9)
      SW(11)=E3(10)
      SW(13)=E3(4)
      SW(15)=E3(5)
      SH=CP*ALOG(SW(10)/SW(11))-RR*ALOG(SW(6)/SW(7))
      SW(14)=SH/G/RR+SW(15)
      WRITE(6,111) (SW(I),I=1,18)
  111 FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'111R')/)
      PR=SW(6)/SW(7)
      CALL RAN(NN,E3,G2,PR,XN)
  104 IF(IDL.LE.0.AND.IDD.LE.0) GO TO 105
      IF(IDL.GT.0.AND.IDR.LE.0) GO TO 106
      IF(IDL.GT.0.AND.IDR.GT.0) GO TO 107
      IF(IDL.LE.0.AND.IDD.GT.0) GO TO 108
  106 CALL SUB(NN,D1,AA2,AA3)
      ID=106
      GO TO 105
  107 CALL SUB(NN,D1,D2,AA3)
      ID=107
      GO TO 105
  108 CALL SUB(NN,AA1,G2,AA3)
      ID=108
  105 RETURN
      END
```

```
      SUBROUTINE GEO(NN,AA1,AA2,AA3,AA4)
      DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN)
      R13=(AA1(3)+AA1(4)+AA3(3)+AA3(4))/2.0
      S13=1.0/R13
      R23=(AA2(3)-AA2(4)+AA3(3)-AA3(4))/2.0
      S23=1.0/R23
      B13=AA1(2)-S13*AA1(1)
      B23=AA2(2)-S23*AA2(1)
      AA3(1)=(B23-B13)/(S13-S23)
      AA3(2)=S13*AA3(1)+B13
      S12=(AA1(2)-AA2(2))/(AA1(1)-AA2(1))
      B12=AA1(2)-S12*AA1(1)
      R34=(AA3(3)+AA4(3))/2.0
      S34=1.0/R34
      B34=AA3(2)-S34*AA3(1)
      AA4(1)=(B12-B34)/(S34-S12)
      AA4(2)=S34*AA4(1)+B34
      PF=(AA2(1)-AA4(1))/(AA2(1)-AA1(1))
      AA4(5)=(1.0-PF)*AA2(5)+PF*AA1(5)
C HEATING
      XK=0.C
      EI=10.0
      EO=15.0
      AA3(6)=0.0
      AA4(6)=0.0
      IF(AA3(1).GE.EI.AND.AA3(1).LE.EO) AA3(6)=XK
      IF(AA4(1).GE.EI.AND.AA4(1).LE.EO) AA4(6)=XK
      PH=(AA2(1)-AA3(1))/(AA2(1)-AA1(1))
      AA3(11)=(1.0-PH)*AA2(11)+PH*AA1(11)
      AA3(7)=0.25
      AA4(7)=0.25

      RETURN
      END


      SUBROUTINE SIML(NN,AL,AR,SW,AA,ID)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      PARAMETER N=18
      DIMENSION AL(NN),AR(NN),SW(N),AA(NN)
      ID=0
      IF(AL(1).EQ.SW(1).AND.SW(2).EQ.AZ) GO TO 108
      IF(AR(1).EQ.SW(1).AND.AR(2).EQ.SW(2)) GO TO 108
      IF(AL(1).GT.SW(1)) GO TO 108
      DDX=SW(1)-AR(1)
      IF(DDX.GT.HX) GO TO 108
      DIA=0.25
      S=(AL(2)-AR(2))/(AL(1)-AR(1))
      B=AL(2)-S*AL(1)
C INITIALISE
      VAS = SW(3)
      VA = SW(4)
```

```
      PA = SW(6)
      PP = SW(7)
      LL=0
 101  CONTINUE
      VBS = VAS
      VB = VA
      PB = PA
      LL=LL+1
      LMAX=5
      LN=LL-LMAX
      IF(LN) 103,103,105
 103  CONTINUE
      R2=0.5*(SW(3)+VBS)+SW(5)
      S2 = 1.0/R2
      B2 = SW(2)-S2*SW(1)
      AA(1)=(B2-B)/(S-S2)
      DIS=SW(1)-AA(1)
      IF(DIS.LT.ZERO) GO TO 108
      VAS=-(CA+CB*(PB/PP))**0.5
      VP=CC*(VAS-1.0/VAS)
      VA=VP+SW(5)
C CONTINUITY FOR A STANDING SHOCK
      V1=VAS
      V2=V1-VP
      D2=SW(9)*V1/V2
      X1=SW(6)/SW(8)
      X2=0.5*(SW(4)*SW(4)*A*A)
      X3=0.5*(VA*VA*A*A)*(1.0+DIS*F/DIA)
      PA=D2*(X1+X2-X3)
C TEST ROUTINE
      TX=0.025
      II=0
      RV=(VA-VB)/VA
      RP=(PA-PB)/PA
      IF(ABS(RV).GT.TX) II=II+1
      IF(ABS(RP).GT.TX) II=II+1
      IF(II) 102,102,101
 102  CONTINUE
 105  CONTINUE
      IF(AA(1).GE.AL(1).AND.AA(1).LT.AR(1)) IO=1
      IF(IO) 108,108,107
 107  AA(2)=S*AA(1)+B
C REDEFINE SHOCK
      SW(1)=AA(1)
      SW(2)=AA(2)
      SW(3)=VAS
      SW(4)=VA
      SW(6)=PA
      SW(8)=D2
      SW(10)=PA/(D2*R)
      SW(12)=SQRT(G*R*SW(10))/A
      SW(16)=0.0
      SW(17)=0.25
      SW(18)=0.2
 109  FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'SIML')/)
      IF(LN) 108,108,104
```

```
104   CONTINUE
      WRITE(6,106) TX,RV,RP,SW(1),SW(2),LMAX
106   FORMAT(1X,5(2X,E10.4),3X,'LMAX=',I5,2X,'SIML')
108   CONTINUE
      RETURN
      END


      SUBROUTINE SOL(NN,AA1,AA2,AA3,AA4,HH3)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      DIMENSION AA1(NN),AA2(NN),AA3(NN),AA4(NN),HH3(NN)
      DO 10 I=1,NN
      HH3(I)=AA3(I)
   10 CONTINUE
      S4=AA4(5)
      DS43=(AA4(6)+HH3(6))/2.0
      T3=HH3(2)
      T2=AA2(2)
      P1=(2.0/(G-1.0))*AA1(4)+AA1(3)
      Q2=(2.0/(G-1.0))*AA2(4)-AA2(3)
      A13=(AA1(4)+HH3(4))/2.0
      A23=(AA2(4)+HH3(4))/2.0
      U13=(AA1(3)+HH3(3))/2.0
      U23=(AA2(3)+HH3(3))/2.0
      D3=HH3(7)
      D1=AA1(7)
      D2=AA2(7)
      E3=HH3(1)
      E1=AA1(1)
      E2=AA2(1)
      DS13=(AA1(6)+HH3(6))/2.0
      DS23=(AA2(6)+HH3(6))/2.0
      F13=(AA1(11)+HH3(11))/2.0
      F23=(AA2(11)+HH3(11))/2.0
      D13=(AA1(7)+HH3(7))/2.0
      D23=(AA2(7)+HH3(7))/2.0
      T3=HH3(2)
      T1=AA1(2)
      T2=AA2(2)
      T4=AA4(2)
      S1=AA1(5)
      S2=AA2(5)
      S3=S4+DS43*(T3-T4)
      P3=P1+(  (G-1.0)*A13*DS13
     1   -(F13*XL/(2.0*D13))*U13*ABS(U13))*(T3-T1)+A13*(S3-S1)
      Q3=Q2+(  (G-1.0)*A23*DS23
     1   -(F23*XL/(2.0*D23))*U23*ABS(U23))*(T3-T2)+A23*(S3-S2)
      AA3(3)=(P3-Q3)/2.0
      AA3(4)=(G-1.0)*(P3+Q3)/4.0
      AA3(5)=S3
20    FORMAT(2X,3(3X,E20.12))
      RETURN
      END
```

```
      SUBROUTINE EIG(NNN,AAA1,AAA2,AAA3,SWL,SWR)
      PARAMETER N=18
      DIMENSION AAA1(NNN),AAA2(NNN),AAA3(NNN)
      PARAMETER NX=15
      DIMENSION AA1(NX),AA2(NX),AA3(NX),AA4(NX)
      DIMENSION SWL(N),SWR(N)
      NN=NNN
      DO 10 I=1,NN
      AA1(I)=AAA1(I)
      AA2(I)=AAA2(I)
   10 CONTINUE
      IF(AA1(2).LT.(0.0)) AA1(2)=AA2(2)
      IF(AA2(2).LT.(0.0)) AA2(2)=AA1(2)
      AA3(3)=(AA1(3)+AA2(3))/2.0
      AA3(4)=(AA1(4)+AA2(4))/2.0
      AA4(3)=AA3(3)
      NM=0
      CALL CHKR(NN,AA1,AA2,AA3,AA4,SWR,NM)
      IF(NM) 109,109,107
  109 CONTINUE
      MM=0
      CALL CHKL(NN,AA1,AA2,AA3,AA4,SWL,MM)
      IF(MM) 110,110,107
  110 CONTINUE
      CALL SUB(NN,AA1,AA2,AA3)
  107 CONTINUE
      DO 11 I=1,NN
      AAA1(I)=AA1(I)
      AAA2(I)=AA2(I)
      AAA3(I)=AA3(I)
   11 CONTINUE
      WRITE(6,2) AAA3
    2 FORMAT(1X,12(2X,E8.3))
      RETURN
      END


      SUBROUTINE SIMR(NN,AL,AR,SW,AA,ID)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      PARAMETER N=18
      DIMENSION AL(NN),AR(NN),SW(N),AA(NN)
      ID=0
      IF(AR(1).EQ.SW(1).AND.SW(2).EQ.AZ) GO TO 108
      IF(AL(1).EQ.SW(1).AND.AL(2).EQ.SW(2)) GO TO 108
      IF(AR(1).LT.SW(1)) GO TO 108
      DDX=AL(1)-SW(1)
      IF(DDX.GT.HX) GO TO 108
      DIA=0.25
      S=(AL(2)-AR(2))/(AL(1)-AR(1))
      B=AL(2)-S*AL(1)
C INITIALISE
      VAS = SW(3)
      VA = SW(4)
```

```
      PA = SW(6)
      PP=SW(7)
      LL=0
  101 CONTINUE
      VBS = VAS
      VB = VA
      PB = PA
      LL=LL+1
      LMAX=5
      LN=LL-LMAX
      IF(LN) 103,103,105
  103 CONTINUE
      R2=0.5*(SW(3)+VBS)+SW(5)
      S2 = 1.0/R2
      B2 = SW(2)-S2*SW(1)
      AA(1)=(B2-B)/(S-S2)
      DIS=AA(1)-SW(1)
      IF(DIS.LT.ZERO) GO TO 108
      VAS = (CA+CB*(PB/PP))**0.5
      VP=CC*(VAS-1.0/VAS)
      VA=VP+SW(5)
C CONTINUITY FOR A STANDING SHOCK
      V1=VAS
      V2=V1-VP
      D2=SW(9)*V1/V2
      X1=SW(6)/SW(8)
      X2=0.5*(SW(4)*SW(4)*A*A)
      X3=0.5*(VA*VA*A*A)*(1.0+DIS*F/DIA)
      PA=D2*(X1+X2-X3)
C TEST ROUTINE
      TX=0.025
      II=0
      RV=(VA-VB)/VA
      RP=(PA-PB)/PA
      IF(ABS(RV).GT.TX) II=II+1
      IF(ABS(RP).GT.TX) II=II+1
      IF(II) 102,102,101
  102 CONTINUE
  105 CONTINUE
      IF(AA(1).GT.AL(1).AND.AA(1).LE.AR(1)) ID=1
      IF(ID) 108,108,107
  107 AA(2)=S*AA(1)+B
C REDEFINE SHOCK
      SW(1)=AA(1)
      SW(2)=AA(2)
      SW(3)=VAS
      SW(4)=VA
      SW(6)=PA
      SW(8)=D2
      SW(10)=PA/(D2*R)
      SW(12)=SQRT(G*R*SW(10))/A
      SW(16)=0.0
      SW(17)=0.25
      SW(18)=0.2
  109 FORMAT((1X,'SW=',2X,9(2X,E10.4),2X,'SIMR')/)
      IF(LN) 108,108,104
```

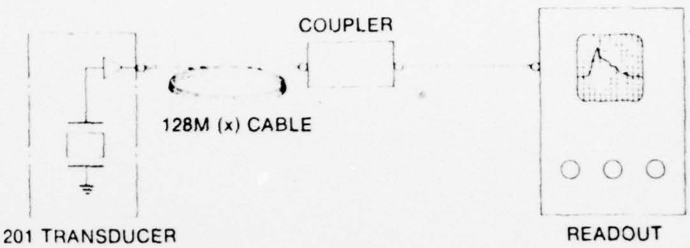
```
      SUBROUTINE CCS(M,X,Y,Z,FACE,IN)
      COMMON /DDD/ G,CP,CV,RF,R,RR,U,A,CA,CB,CC,HX,AZ,ZERO,F,XL
      PARAMETER NZ=4
      PARAMETER NX=15
      DIMENSION X(M),Y(M),Z(M)
      DIMENSION FACE(NZ),AB(NX),YY(NX)
      IN=0
      XHX=4.0
      IF(Y(1).LT.FACE(1)) GO TO 200
      XXL=X(1)-FACE(1)
      IF(XXL.GT.XHX) GO TO 200
      IF(X(1).EQ.FACE(1).AND.X(2).EQ.FACE(2)) GO TO 200
      IF(Y(1).EQ.FACE(1).AND.Y(2).EQ.FACE(2)) GO TO 200
      Z(3)=(X(3)+Y(3))/2.0
      Z(4)=(X(4)+Y(4))/2.0
      AB(3)=Z(3)




      CALL GEO(M,X,Y,Z,AB)
C  RIGHT LEG ONLY
      S23=(Z(2)-Y(2))/(Z(1)-Y(1))
      B23=Y(2)-S23*Y(1)
      RCS=FACE(3)
      SCS=1.0/RCS
      BCS=FACE(2)-SCS*FACE(1)
      E=(BCS-B23)/(S23-SCS)
      T=S23*E+B23
      IF(E.GE.Z(1).AND.E.LE.Y(1)) GO TO 101
      GO TO 102
  101 CONTINUE
      IN=101
      PL=(2.0/(G-1.0))*X(4)+X(3)
      QR=(2.0/(G-1.0))*Y(4)-Y(3)
      SL=X(5)
      SR=Y(5)
      CAL=0.25*(G-1.0)*(SL-SR)
      QL=(PL+QR)*TANH(CAL)+QR
      PR=(QR-QL)+PL
      V=(PR-QL)/2.0
      C=0.25*(G-1.0)*(PR+QL)
      YY(1)=E
      YY(2)=T
      YY(3)=V
      YY(4)=C
      YY(5)=X(5)
      YY(6)=0.0
      YY(7)=0.25
      YY(11)=0.2
      CALL SSS(M,X,YY,Z)
      FACE(1)=E
      FACE(2)=T
      FACE(3)=V
      WRITE(6,1) FACE
    1 FORMAT(1X,4(2X,E10.4),2X,'INTERFACE')
  102 CONTINUE
  200 CONTINUE
      RETURN
      END
```

```
104   CONTINUE
      WRITE(6,106) TX,RV,RP,SW(1),SW(2),LMAX
106   FORMAT(1X,5(2X,E10.4),3X,'LMAX=',I5,2X,'SIMR')
108   CONTINUE
      RETURN
      END


      SUBROUTINE SSS(NN,AA1,AA2,AA3)
      DIMENSION AA1(NN),AA2(NN),AA3(NN)
      DIMENSION HH3(15),AA4(15)
      AA4(3)=AA3(3)
      AA3(3)=(AA1(3)+AA2(3))/2.0
      AA3(4)=(AA1(4)+AA2(4))/2.0
      LL=0
101   CONTINUE
      LL=LL+1
      LMAX=5
      LN=LL-LMAX
      IF(LN) 103,103,105
103   CONTINUE
      CALL GEO(NN,AA1,AA2,AA3,AA4)
      CALL SOL(NN,AA1,AA2,AA3,AA4,HH3)
C     TEST ROUTINE
      TX=0.001
      II=0
      RV=(AA3(3)-HH3(3))/AA3(3)
      RA=(AA3(4)-HH3(4))/AA3(4)
      IF(ABS(RV).GT.TX) II=II+1
      IF(ABS(RA).GT.TX) II=II+1
      IF(II) 102,102,101
102   CONTINUE
      GO TO 104
105   WRITE(6,106) TX,RV,RA,AA3(1),AA3(2),LMAX
106   FORMAT(1X,5(2X,E10.4),3X,'LMAX=',I5,2X,'SSS')


104   CONTINUE
      CALL PPP(NN,AA1,AA3)
      AA3(12)=LL
      RETURN
      END
```

APPENDIX D

201 SERIES MINI-GAGE

Typical PIEZOTRON® Pressure Sensing System



Couplers

To complete the system a wide choice of couplers is offered in the 548 and 549 series. Optional filters and several types of power inputs are available. Model 587D Coupler provides increased capability. Please refer to our Coupler Data Sheet for details.

In addition Models 583, 503D and 504D Laboratory Amplifiers are offered with extensive versatility and many options for more complete pressure studies.

Specifications			**Model Variation**		
PERFORMANCE	UNITS	201B1	201B2	201B4	201B5
Pressure Range, 5V out	psi	5,000	500	200	100
Overrange	psi	7,500	750	300	150
Resolution (noise)	psi rms	0.05	0.005	0.002	0.001
Maximum Pressure	psi	15,000	5,000	2,000	1,000
Sensitivity	mV/psi	1	10	25	50
Linearity, B.F.S.L.	%	±1	±1	±1	±1
Resonant Frequency, nom.	kHz	500	500	500	250
Rise Time, 10-90%	μ sec	1	1	1	2
Time Constant, R.T.	sec	1,500	400	200	100
Low Frequency Response, −5%	Hz	0.0003	0.001	0.0025	0.005
High Frequency Response, +5%	Hz	100,000	100,000	100,000	50,000
ENVIRONMENTAL			**Common Specs**		
Vibration Sensitivity, max.	psi/g	0.002	0.002	0.002	0.002
Shock, 1 ms	g	5,000	5,000	5,000	5,000
Vibration Limit	g	500	500	500	500
Temperature Range	°F	−65 to 280	−65 to 280	−65 to 280	−65 to 280
Temperature Sensitivity Shift	%/°F	0.03%	0.03%	0.03%	0.03%
ELECTRICAL					
Output Current, min.	mA	2	2	2	2
Polarity, pressure increase		Negative	Negative	Negative	Negative
Bias Voltage	V	11 ±2	11 ±2	11 ±2	11 ±2
Circuit Return		Case	Case	Case	Case
Output Impedance, max.	ohms	100	100	100	100
MECHANICAL					
Weight	gms	< 10	< 10	< 10	< 10
Case and Diaphragm Material		Stainless St.	Stainless St.	Stainless St.	Stainless St.
Mounting Torque	in-lb	24	24	24	24
Sealing		All Welded	All Welded	All Welded	All Welded
POWER SUPPLY					
Constant Current Source	mA	4 ±1	4 ±1	4 ±1	4 ±1
Supply Ripple, max.	mV rms	25	25	25	25
Supply Voltage, no load	VDC	20-30	20-30	20-30	20-30
Source Impedance, nom.	ohms	250 k	250 k	250 k	250 k